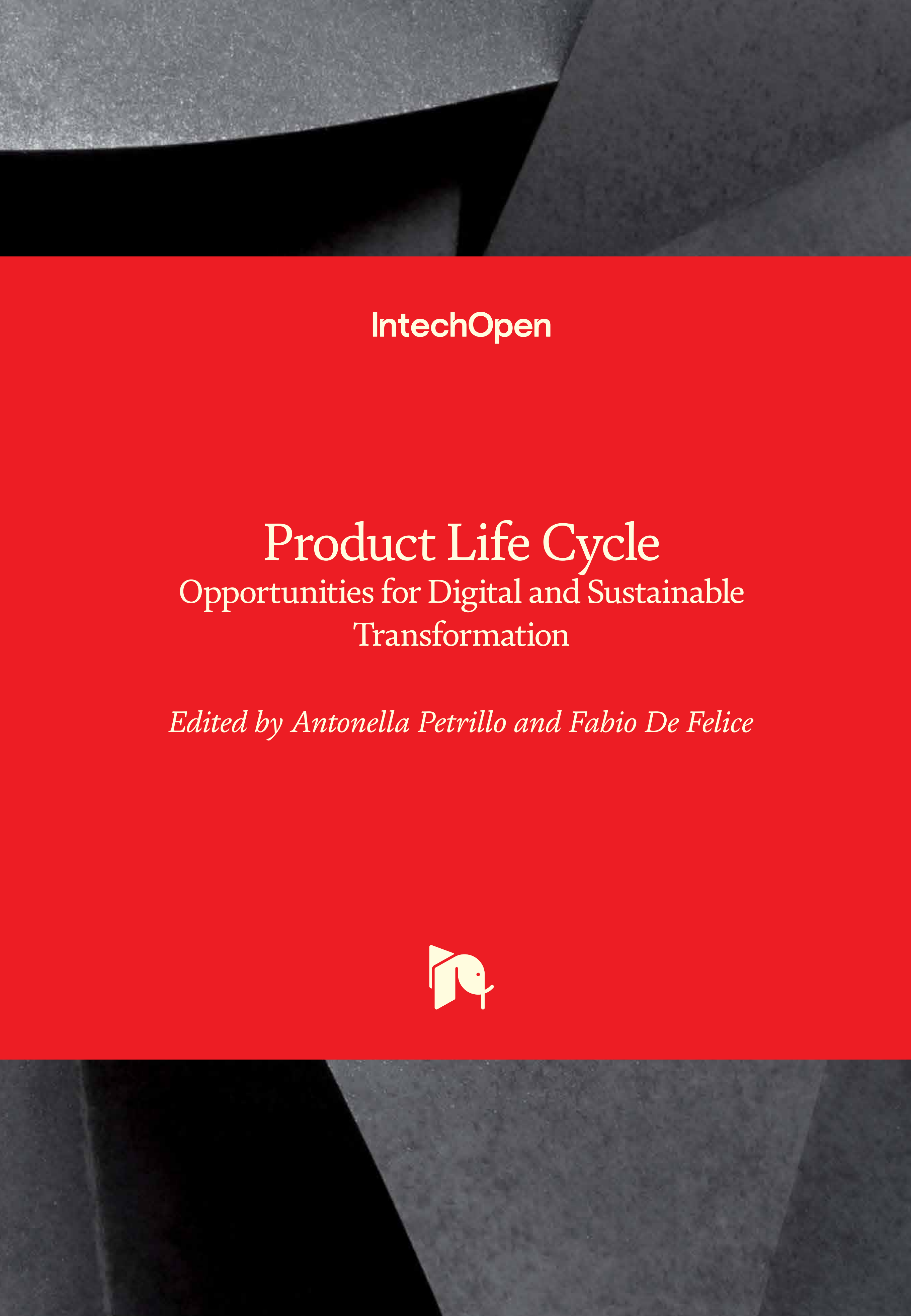

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Product Life Cycle

Opportunities for Digital and Sustainable Transformation

Edited by Antonella Petrillo and Fabio De Felice

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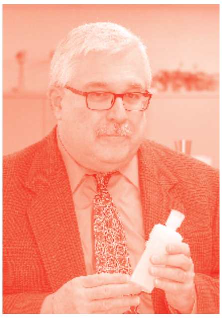

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Contents

Preface

Today we are living at a decisive moment in the fight to promote sustainability. We must be aware that during the COVID-19 pandemic, "*sustainability problems did not go on vacation. All values have exceeded the limits, they are in the red zone.*" The problem of sustainability is an "old" problem. For almost three decades, the United Nations has been bringing together almost all the countries of the world for global climate summits called "Conference of the Parties" (COP). Since then, climate change has gone from being a marginal issue to becoming a global priority. The annual UN climate conference, COP26, reminds us that the issue of sustainability is now an issue that requires urgent measures, a change of course by the G20 summit. From Nepal to Bermuda to Madagascar, *"where according to many the first famine induced by climate change in history is occurring*," the effects of the "*worsening of the earth's climate are visible everywhere in the world*." In our age, the development of a *competitive* and *resilient society* has two main determinants: a pervasive digital transformation and the growth of environmental and social sustainability of human activities. These two development paradigms not only complement each other within a widely shared vision of development, but they also reinforce each other in a synergistic relationship. In this scenario, it is clear that methodologies and tools that serve to define the product, manage its evolution, and monitor business processes are the keys to success for any company and production sector. It must also be clear that a holistic view of the product presupposes a strategic management of data, information, processes, and related resources. Certainly, digital technologies play a decisive role in the green transition. Speed, flexibility, and punctuality in the management of activities often translate, for example, into a sharp drop in production waste. The need to measure the environmental impact of digital business is a topical issue for those involved in sustainability. We are aware of the advantages that sustainability and digitalization bring to companies: the first, now essential in a vision of serious business development, serves to transform the products and services offered so that they have as minimal an environmental impact as possible. By this, we mean reducing pollution from production activity and reducing waste by increasing the use of secondary raw materials. This can be accomplished via careful design of products' life cycles and putting the future of people and the planet first. Companies should perceive the power of sustainability in the development of a future vision that brings benefits to the whole system, both inside and outside the organization. The topic of sustainability is getting hotter, especially for companies that find themselves having to meet the demands of a market that is sensitive to the reduction of all environmental impacts. The pandemic, in fact, has clearly shown companies the importance of an efficient, resilient supply chain; however, the issues of environmentally friendly production and sustainability still deserve attention. A clear vision and environmental culture are lacking because, even today, companies are motivated to act to improve the environment essentially by compliance with government regulations and the opportunity to achieve profit growth. This book is a useful resource for anyone who deals with these issues. We hope that it will provide useful ideas, techniques, and methods for further research.

Special thanks to all the authors who contributed to the success of the project. On behalf of all, we thank the following authors: Dr. Shinozaki Akira, Dr. Olanrewaiu Oludalapo, Dr. Minguez Rikardo, Prof. Augusto Bianchini, and Dr. Udokporo Chinonso. We are also grateful to the manuscript reviewers for their effort, time, and invaluable suggestions. Our special thanks to the staff at IntechOpen, especially Commissioning Editor Anja Filipovic, Author Service Manager Martina Ivancic, and Darko Hrvojic for their support throughout the publishing process.

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Chapter 1

Product Lifecycle: Social and Political Reflections from the Digital and Sustainable Perspectives

Fabio De Felice and Antonella Petrillo

Abstract

Digitalization and sustainability are the drivers of the global development of the future that have slowly conquered the agendas of governments and organizations on every continent. In this context, the pandemic has proved to be a powerful technological accelerator, helping to give a greater boost to these drivers, "guiding" leading the productive and economic sector throughout the world. Today the sustainability and digitalization represent the indispensable prerequisites to add economic, environmental, and social sovereignty. In fact, the scenario that the Coronavirus is leaving us foreshadows the need not to be satisfied with reaching targets for reducing greenhouse gas emissions, but to imagine "global" governance for the development of business models based on the new digital frontiers. Thus, what are the challenges for achieving the paradigms of sustainability and digitization in this new era? And what are the tools for a "digicircular" transformation? The aim of this chapter is to investigate these issues. To this end, it should be noted that, in this chapter, our aim is not to present an analysis of literature in the classical sense but rather political and social reflections.

Keywords: digitalization, sustainability, business, covid, environment, society, economy

1. Introduction

The pandemic has highlighted the importance of responsible use of resources in all sectors. The production sector is no exception. COVID-19 has given a push to transfer the circular paradigm from the economy to politics, precisely because the pandemic has planetary extension and repercussions. The key principle of the circular economy is the adaptation of economic cycles to natural cycles. A new paradigm is proposed as an innovative and advanced solution to combine growth in consumption and demand for goods with environmental sustainability [1]. This means rethinking the way in which we use matter and energy from design to production, from consumption to the management of the so-called "waste". In this context, with reference to the concept of waste, it would be desirable to speak of a "waste resource", thus overturning the very meaning of the term [2]. Today, it is quite clear that circular solutions will not be able to spread without the support of digital technologies and infrastructures, within an extremely broad reference perimeter: transport, ports, digital infrastructures, energy, and electricity networks [3]. Digital transformation and sustainability should provide for interaction and integration between new physical and digital technologies or artificial intelligence, internet of things, augmented reality, additive manufacturing, both on the network side and on the digitalization of processes [4]. Positive repercussions of the sustainable transition on the economy are realistically achievable only on the condition of having facilities capable of allowing the exchange of resource flows through transcontinental infrastructures. A scenario that can only be obtained under the condition of a colossal exchange of information (big data) that will make it possible to meet the needs and demand for the well-being of a world population which, from 1970 to 2017, has increased by 2 times and world consumption of materials increased by 4 times with all the consequent negative effects in terms, for example, of waste production [5]. However, there has been talking of digitalization of infrastructures since the end of the nineties, but today we are quite far from the minimum goal of digitizing the backbones and essential resources of our planet [6]. The question is: how to give a metric, a dimension, a "measurability" of the quantities that can lead us to sustainability? Today, technology could help achieve this goal; for example, thanks to the immense computing capabilities of a quantum computer (quantum computing from IBM and Google are already available today for various simulations) or the evolution of deep learning. But all this may only be possible if the data is available. The key to building economic and social resilience, therefore, lies in digitization, which is the dominant element around which the collective future takes shape [7]. Thus, what are the challenges for achieving the paradigms of sustainability and digitization in this new era? And what are the tools for a "digicircular" transformation? The aim of this chapter is to investigate these issues. To this end, it should be noted that, in this chapter, our aim is not to present an analysis of literature in the classical sense but rather political and social reflections.

The rest of the chapter is organized as follows: Section 2 intends to analyze the link between sustainability, digitalization from a product life cycle perspective; Section 3 outlines how to design a "digicircular" future; Section 4 tries to summarize some challenges for digitalization and sustainability. Finally, in Section 5 the main conclusions of the study are outlined.

2. Sustainable sovereignty: condition for digital sovereignty

Digitization and sustainability are among the most discussed topics in recent years and their simultaneous implementation will constitute the challenge and opportunity for the near future [8]. It is therefore essential to enhance the evolution over time of the links between these two and to understand if there are technologies that favor the creation of circular economies and, if so, what they are. As known the main technologies are: internet of things, cloud computing, augmented reality with artificial intelligence, additive manufacturing, horizontal and vertical integration, cybersecurity, autonomous robots, simulation/digital twin, and big data analytics [9]. From our point of view, it is interesting to analyze the link between sustainability, digitalization/technologies from a product life cycle perspective [10]. Thus, an investigation on Scopus, the largest abstract and citation database of peer-reviewed literature has been carried out in this research. The database was queried using the Boolean operators AND and OR as the following string shows: (TITLE-ABS-KEY (sustainability) AND TITLE-ABS-KEY (digitalization) OR TITLE-ABS-KEY (internet AND of AND things) OR TITLE-ABS-KEY (cloud AND computing) OR TITLE-ABS-KEY (artificial AND intelligence) OR TITLE-ABS-KEY (augmented AND reality) OR TITLE-ABS-KEY (additive AND manufacturing) OR TITLE-ABS-KEY (horizontal AND vertical AND integration) OR TITLE-ABS-KEY (cybersecurity) OR TITLE-ABS-KEY (robot) OR TITLE-ABS-KEY (simulation) OR TITLE-ABS-KEY (big AND data) AND TITLE-ABS-KEY (product AND life AND cycle)). In detail, all the articles that had the string in the title, in the abstract, and in the keywords were selected. The search returned 384 documents. The 384 papers were analyzed not with the intent of developing a detailed literature review. Rather, the purpose of this investigation was to identify challenges and future trends with respect to two aspects, the most used keywords, and publication sources. But before analyzing the above features it is remarkable to note the distribution of documents over time. Documents are distributed from 1999 to 2021 (in progress), but obviously only in the last 5 years has there been an increase in the number of publications as shown in **Figure 1**.

To underestimate the interconnections and trends relating to the concepts of sustainability and digitization from a product life cycle perspective, has been used VOS viewer software [11]. In particular, co-occurrence analysis and bibliographic coupling were performed. Analysis of keyword co-occurrence is the bibliometric method used to map the research field. The process of creating keyword networks and clustering keywords is aimed at identifying the main research fields in the area of technologies (i.e., internet of things, big data analytics and, recently, also additive manufacturing) and environmental sustainability (see **Figure 2**).

In detail, it emerged that Internet of Things technologies are mainly used to extend the life cycle of the product but they prove to be a good solution also for the management of waste collection and recovery operations in the supply chain [12–14]. While, Big Data Analytics technologies are useful to use resources efficiently, to collect or manage data relating to the life cycle of products, and to develop new business models in a circular perspective. Artificial Intelligence can contribute to the implementation of a sustainable process in accelerating the development of products, components, and the choice of sustainable materials through assisted design processes that allow rapid prototyping and testing. It also favors the implementation of circular business models [15, 16]. Additive Manufacturing can incentivize sustainability thanks to the support it offers in terms of product life cycle management, recycling processes, and digitalization of production. In other words, a factory should be designed to be completely connected: from machinery to integrated processes, which will be combined with Artificial Intelligence algorithms [17, 18]. **Figure 3** shows a bibliographic

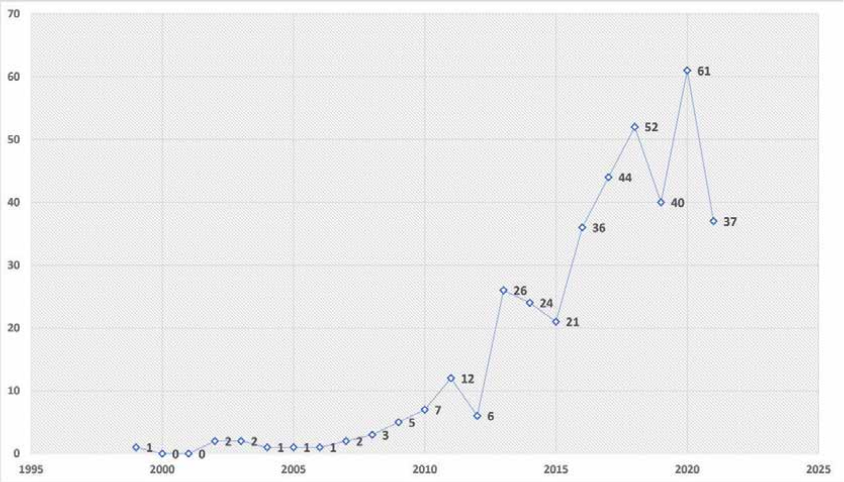

Figure 1.
Documents by years (source Scopus).

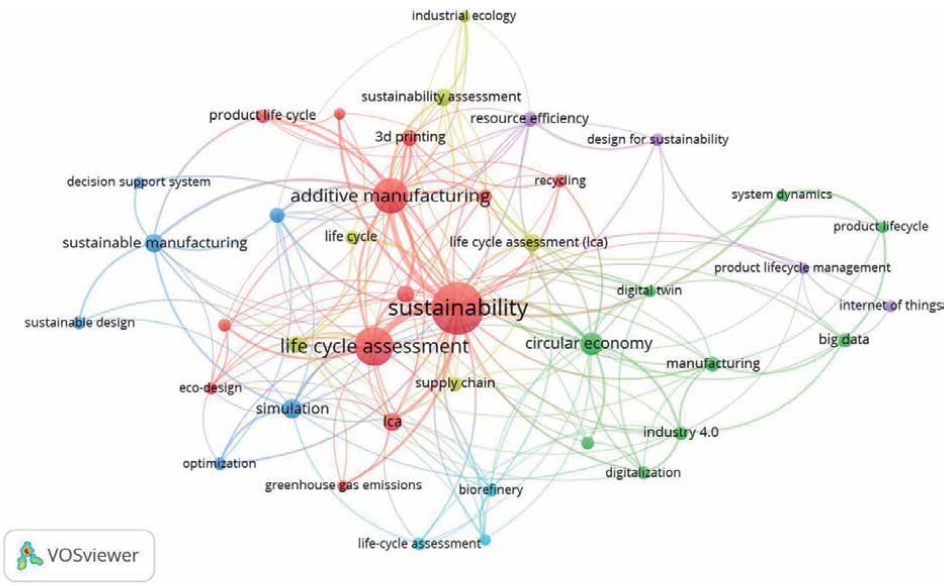

Figure 2.
Co-occurrence analysis.

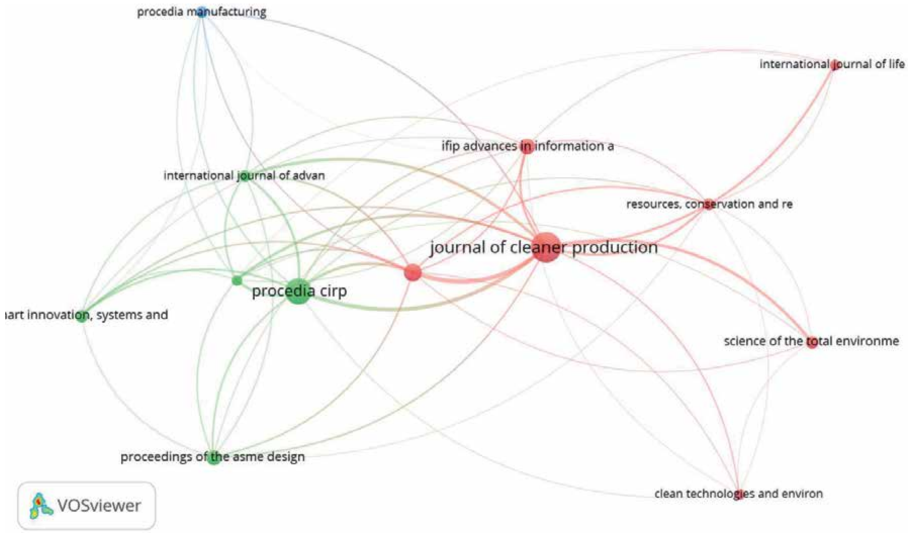

Figure 3.
Bibliographic coupling.

coupling analysis considering the sources. It emerges that the *Journal of Cleaner Production* is one of the most attractive scientific references for these issues. The result is not surprising because in the scientific community the journal is recognized as one of the best, interdisciplinary journals in which scientific works are encouraged that combine three key elements: reduction, environmental, and sustainability.

The analysis shows that there will be no emerging technology on the others, but an integration of technologies. A hybridization of digital technologies that will favor the transition towards sustainable production in view of product life cycle management is needed [1, 19, 20].

3. Designing a "digicircular" future

It is clear that digitization can be an opportunity to accelerate the sustainability processes connected to digitalization. The point now is to understand how to move from a qualitative to a quantitative approach [21]. The problem is not entirely secondary, it is indeed extremely important. In fact, many organizations and companies struggle to understand what is circular from what is not. A paradigm shift is needed. A new mindset to redesign the model for the future, adopting the circular economy model on a national and international scale. From this perspective, digital technologies represent an opportunity to identify new business models [22]. The combination of technologies helps to evolve businesses into a virtuous circle of improvement. At the same time, digital technologies help not to "make mistakes". Just think of the potential of digital twins that allow us to simulate real systems in virtual environments by comparing multiple scenarios, optimizing resources, time, and costs. However, we must be clear that there is no single model valid for all organizations and companies [23]. It is essential to know the market in order to have all the information and data necessary to define the most suitable business model. Today a large amount of data available is lacking the right information useful for making decisions and making the system as a whole predictive. However, moving to a circular economy model is a complex process that requires the use of appropriate measurement and improvement tools. The standardization processes launched for some years by the UNI and ISO commissions (UNI/CT 057 Commission and ISO/TC 323—Circular economy) provide a valid contribution in starting to speak the same common language. It is clear that methods and tools are needed to define the product and manage its evolution from the sustainability perspective. In this regard, it is essential to monitor business processes by sharing information between the internal functions with all the stakeholders (designers, suppliers, distributors, customers) [24]. Thus, quantifying sustainability in the perspective of product life cycle represent a key factor as shown in **Figure 4**.

QUANTIFY sustainability

1. Knowledge of the sector and processes
2. Identification of resource flows
3. Application of unique standards
4. Measurement and selection of reference indicators (KPIs)
5. Identification of criticalities
6. Definition of improvement plans (PLAN-DO-CHEK_ACT)

Principles, frameworks and management systems
Guides for implementation and sectoral applications

Figure 4.
Global challenges in terms of enabling factors and the value chain.

4. Challenges for digitalization and sustainability

The challenges of digitization and sustainability require an integrated approach to legislative activity and coordination and cooperation activities worldwide. In this sense, it is also necessary to promote new initiatives to regulate artificial intelligence, among others, considered as one of the main technologies useful for the development of circular models, with particular attention to the ethical implications deriving from the use of algorithms. Another aspect to be considered among the challenges for the circular economy is the development of global digital platforms as a tool for a virtuous use of resources capable of intercepting all the stakeholders in the supply chain from a global "resources" market perspective [25]. In this way it will also be possible to optimize costs and waste at the national and international level, in compliance with recognized global standards as well as customized solutions, resulting from applications of global scientific instruments. The real challenge is that everyone in their area (production, suppliers, and customers) should contribute to the "system", generating value downstream and upstream to enable the factors for the transition and thus achieve sustainable sovereignty. In fact, a globalized supply chain designed to use fewer materials is more resilient. In this way, a collaborative approach is adopted both with companies that treat waste and with suppliers of raw materials, to achieve win-win models. Producing what is needed when needed (e.g., the use of 3D printers, with the consequent decrease in the movement of materials and goods and an increase in dematerialization), thinking in terms of services and not just products, are central factors and fundamental assumptions in a vision of a globalized and integrated supply chain [26]. Obviously, in this perspective, digitization along the value chain represents an essential element for the control, planning, and forecasting of business activities that influence competitive factors from a circular economy perspective. The information generated by digital technologies supports the transition to a circular economy/sustainability through the identification of business opportunities and the enhancement of resources with a view to benefits and costs. A holistic vision of the product presupposes strategic management of data, information, processes, and resources relating to each phase, as shown in **Figure 5**.

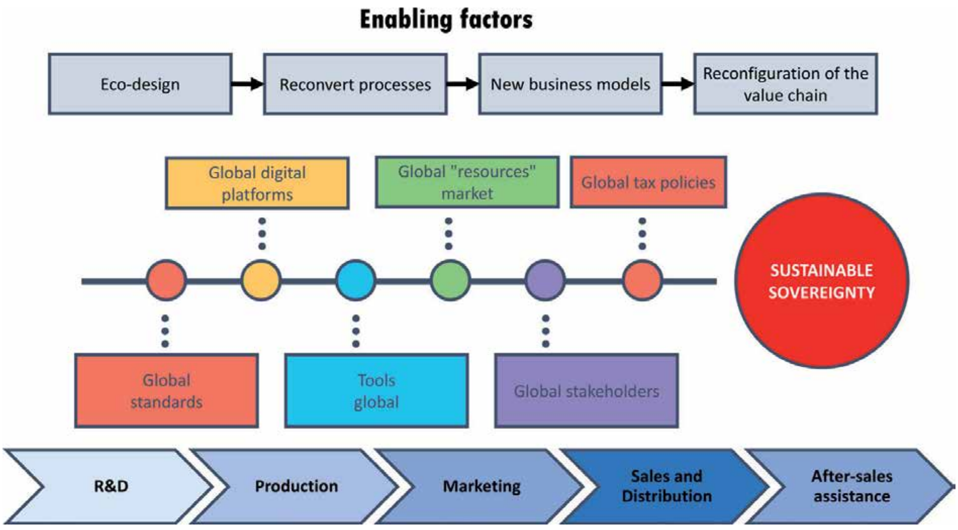

Figure 5.
Enabling factors of Sustainable Soverignty.

In other words, "digicircular actions" horizon can be summarized as follows: (1) Create a taxonomy for the international circular economy; (2) Integrate environmental, social, and economic policies; (3) Promote standards and certifications; (4) Use transparent tools (LCA, EPD, …) and (5) Strengthen measures for the development of the bioeconomy.

5. Conclusions

Digital and Sustainable are among the most discussed topics in recent years and their simultaneous implementation will be a challenge and opportunity for the near future. Digital transitions should help redraw the boundaries of our world in a more "*sustainable*" way. Of course, technology itself does not mobilize itself towards transformations of sustainability, since a strong political will is needed to create pathways capable of engaging these perspectives. Furthermore, digital technologies are not innocent in the progressive worsening of the state of our planet and the growth of greenhouse gas emissions. Therefore, there is also a topic related to the impact of digital technologies. The perception of the relationship between risk and benefit remains a complicated aspect to assess. However, in the long term, the benefits will outweigh the risks, as it is easy to imagine if the use of technologies is accompanied by responsible use. In conclusion, the present study underlines the link between sustainability and digitalization and make people understand that correct management of the life cycle requires innovation. Technologies, in fact, are able to optimize the use of resources, reducing waste, simplifying processes, and making the use of infrastructures sustainable. It is, therefore, necessary to connect these two issues to achieve what will be the smart sustainable factories capable of bringing a triple economic, environmental and social advantage.

Conflict of interest

The authors declare no conflict of interest.

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Chapter 2

Precision Polishing Techniques for Metal Molding Dies and Glass Forming Technology “Slumping Method”

Akira Shinozaki and Junpei Kinoshita

Abstract

Precision manufacturing techniques are required for the fabrication of small and large optical components in various fields. To prepare molding dies with highly precise geometric shapes and surface roughness that are used in certain molding processes, polishing techniques have been investigated for many materials. In this research, the polishing techniques used for a SUS310S stainless steel molding die for the glass forming technology “slumping method” were investigated. The surface roughness of the polished SUS310S molding die surface was below Rz = 120 nm (P–V), Ra = 20 nm after 35 h of polishing with 0.5% alumina polishing liquid under a pressure of 1.7 kPa. In addition, the centerless polishing machine was designed and manufactured to polish cylindrical molding die surfaces with same polishing conditions. As the result of using cylindrical molding dies that made by this centerless polishing machine, the surface roughness of the glass plate formed using the slumping method with the polished molding die was below Ra = 20 nm. These results indicate that the surface roughness of the molding die had a small effect on the glass plate surface formed using the slumping method.

Keywords: precision polishing, molding die, glass forming, surface roughness, slumping method, manufacturing

1. Introduction

The X-ray astronomical satellite “ASTRO-H” was launched in February 2016 and carried hard and soft X-ray telescopes. However, an accident that occurred during adjustment caused the satellite to break up, and the project was canceled. For the launch of the successor by the Japan Aerospace Exploration Agency (JAXA) in 2020, an X-ray telescope needs to be rapidly fabricated at a lower cost than the ASTRO-H project. The X-ray astronomical satellite consists of over 1,200 super mirror pieces in a telescope with a diameter of 600 mm [1–3]. These mirrors are prepared using the “replica method” that presses and transcribes the mirror material on the surface into thin aluminum plates [4–7]. These techniques using precision molding dies [8–11] have also recently been applied not only for X-ray telescopes but also for various other optical components that require rapid and low-cost manufacturing.

Authors previously proposed the use of the “slumping method” as a thermo glass forming method to achieve rapid and low-cost manufacturing of optical components [12]. The slumping method can be used to manufacture next-generation X-ray telescope; in addition, it can be used for shape forming of glass super mirrors and other optical components. In our previous studies, a SUS304 stainless-steel molding die with nanoscale surface roughness was successfully prepared using the slumping method [13].

In this study, the precision polishing process for a SUS310S stainless-steel molding die as a heat-resisting metal was investigated using various polishing pressures, polishing times, and surface roughnesses. This technology was developed to manufacture super mirrors of space telescopes used in the field of aerospace. Therefore, the accuracy required for these products are so high levels such as “some nano meters or sub nanometers”. By considering these results, it may be possible to open up new using fields of application with precision manufacturing and designing technology in the future.

2. Structure of X-ray telescope

Figure 1 shows a structure of the X-ray telescope structure [1]. The diameter of the X-ray telescope cylinder used in ASTRO-H is approximately 600 mm and consists of more than 1,200 super mirror pieces. The X-ray wavelength is below 1 nm, and the X-rays enter at an angle of less than 1° and are reflected twice by the interior surface of the mirror. The reflected X-rays are then focused on a detector positioned 8 m away. The super mirrors with a multi-layer film of “platinum carbon” used to reflect the X-rays by “Bragg reflection [1]“are approximately 0.2 mm thick and very smooth. The super mirrors are the main components of the X-ray telescope; however, their manufacture is difficult because of their arc-line shape and the highly precise surface roughness needed to enable detection of the X-rays. To meet these specifications, high-precision techniques are required to prepare the molding dies used to fabricate the super mirrors.

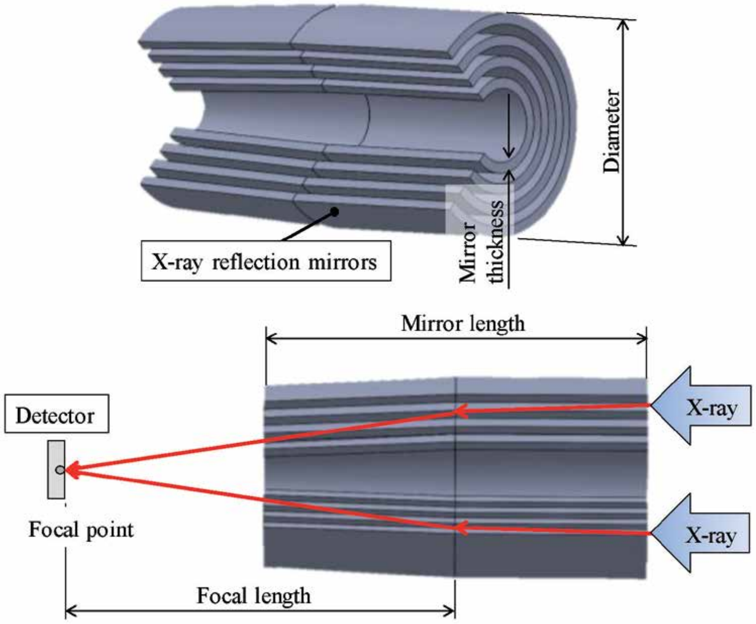


Figure 1.
Structure of the X-ray telescope structure [1].

3. Mechanism of "slumping method"

The "slumping method" was proposed for the manufacture of the base shape of super mirrors and other optical components. The slumping method is a glass forming process with heating at the glass softening point [12]. **Figure 2** presents an overview of the "slumping method". A glass plate is placed on a molding die that has the shape of the optical component. The glass plate is then heated and thermoformed along the molding die. The surface roughness of the molding die is critical because it may be transcribed to the glass surface if it is rough. Therefore, high-precision polishing of the molding die should be performed to achieve a highly precise surface roughness. In addition, the molding die must also exhibit good heat resistance to enable its exposure to repeated heating processes.

4. Precision polishing of SUS310S molding die

In the slumping process, the use of stainless steel SUS310S as the molding die material is proposed because of its good heat resistance. In our previous study, a SUS304 stainless-steel molding die with nanoscale surface roughness was successfully prepared [13]. However, intergranular corrosions occurred at about 600°C on its surface after the slumping process, therefore, in this work, stainless steel SUS310S was selected because of its improved heat resistance [14, 15]. The temperature of 600°C is a softening one used to transform glass plates, in the case of using SUS304, these temperatures almost accords. Therefore, the SUS310S material that intergranular corrosion temperature is over 750°C was selected as an improvement research [16]. By this background, precision polishing experiments were conducted using various polishing pressures, polishing times, and surface roughnesses.

4.1 Precision polishing experimental procedure

Table 1 summarizes the conditions used for the precision polishing experiments, and **Figure 3** presents an overview of the precision polishing experiment. The precision polishing was performed using a bench-type polishing machine (MA-200, Musashino Denshi). The end surfaces of the stainless steel SUS310S workpieces

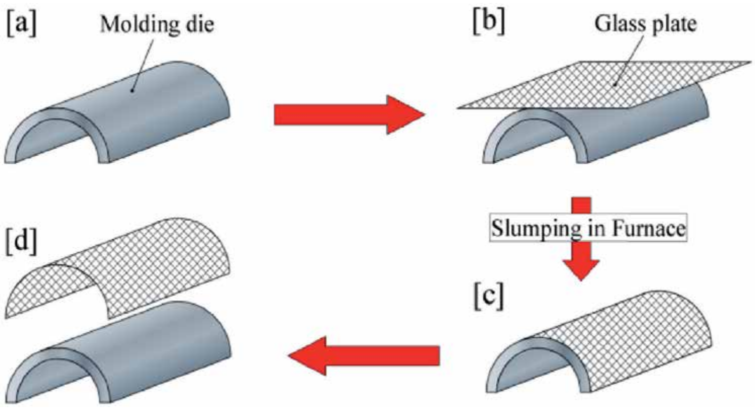


Figure 2.
Outline of the glass forming techniques "slumping method". (a) Preparation of molding die. (b) Processing set up. (c) Demolding process. (d) Deformation process.

Polishing machine	Bench type polishing machine MA-200, Musashino denshi, Co., Ltd
Workpiece material	Stainless steel SUS310S in JIS
Polishing pad	Suede type
Polishing liquid	0.5% – alumina polishing liquid (Abrasive grain size = 5 μm)
Polishing condition	Polishing pressure 1.7 [kPa]

Table 1.
Experiment conditions.

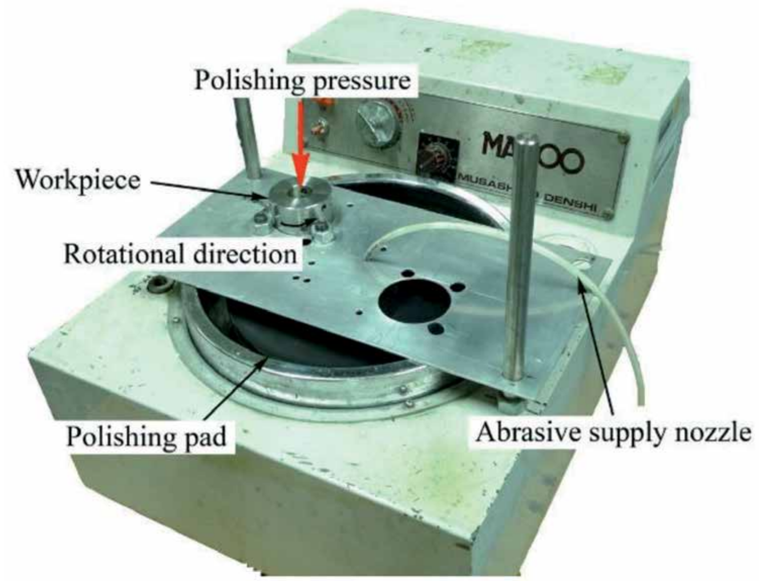


Figure 3.
Overview of precision polishing machine and experiment.

(50 mm diameter, 10 mm thickness) were polished, as shown in **Figure 4**. The polishing pad was a suede-type pad, and the polishing liquid was a 0.5% alumina (# 3000) mixture dispensed at a rate of 50 ml/h by a tube pump (PST110, Iwaki). The surface roughness of the workpieces and formed glass plates were measured using a surface roughness tester (SJ-201, Mitsutoyo) and 3D optical surface profiler (NewView7100, ZYGO). Measurements were taken approximately 5, 12, and 20 mm from the center of the workpiece for the "inside", "center", and "outside" positions, respectively.

4.2 Results of precision polishing for SUS310S

Figure 4 shows the workpieces before and after polishing. Cutting grooves were apparent on the workpiece surface before polishing, as shown in **Figure 4(a)**; these grooves were formed over the entire surface by the previous cutting process. Generally, it has been found that a machining for stainless steels called "hard to cut materials" is difficult to make smooth surface, because diamond bites cannot be used in ultra-precision cutting process [17, 18]. However, after 37 h of polishing, the workpiece had a mirror surface with the grid pattern of the under sheet, as observed in **Figure 4(b)**. Comparison of the surfaces reveals that the precision polishing process reduced the surface roughness.

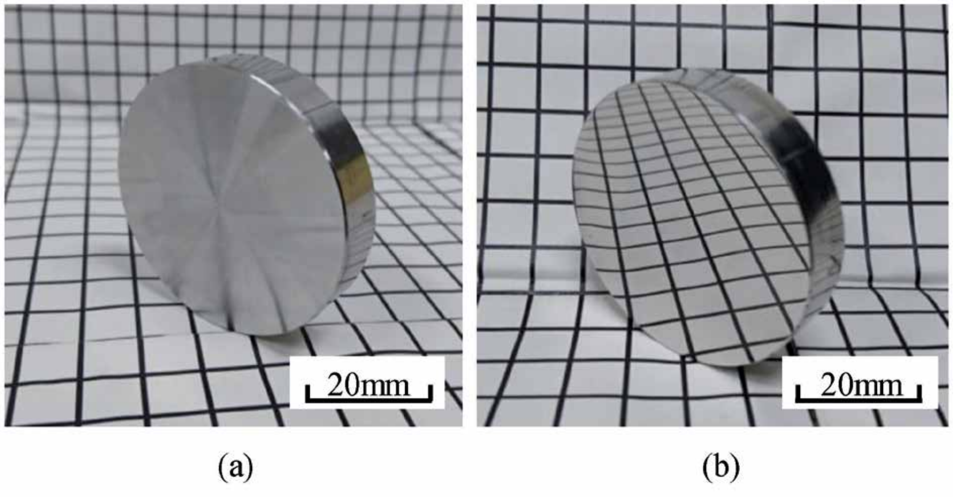


Figure 4.
Comparison of before and after polishing workpieces. [SUS310S, 0.5%-Al_2O_3 polishing liquid, 1.7 kPa]. (a) before polishing. (b) after polishing.

Figure 5 presents shows the relationship between the surface roughness *Rz* of the polished SUS310S surface and polishing time for a polishing pressure of 1.7 kPa. When the precision polishing process was performed for 1 hr., the surface roughness of the outside region was the smallest of all the regions with *Ra* = 0.07 μm and *Rz* = 0.64 μm, as shown in **Figure 5(b)**. After more than 2 hrs of polishing, repeated small variations in the surface roughness were observed and the surface roughness was reduced equally over the entire surface. After approximately 15 hrs of precision polishing, the surface roughness was almost constant at *Ra* = 0.03 μm and *Rz* = 0.25 μm. After that, the surface roughness gradually decreased, and finally, a surface roughness of *Ra* = 0.02 μm and *Rz* = 0.16 μm was achieved after 37 hrs of precision polishing.

In our previous study on precision polishing with a polishing pressure of 0.7 kPa (only the pressure of the die weights without additional pressure), the surface roughness of the outside region was less than 1.0 μm after 5 hrs of polishing [12, 13]. However, in the current study using a pressure of 1.7 kPa, the surface roughness was smaller than *Rz* = 1.0 μm after less than 2 hrs; these results indicate that the polishing efficiency was improved with higher polishing pressure.

Figure 6 compares the surface roughness (a) before polishing, (b) after 1 h polishing, and (c) after 37 hrs polishing for a polishing pressure of 1.7 kPa. **Figure 6(a)** confirms that the tool feed interval roughness resulted in the cutting grooves observed in **Figure 4(a)**, for which the surface roughness was *Ra* = 0.4 μm and *Rz* = 2.7 μm. After 1 h polishing, the surface roughness decreased (*Ra* = 0.07 μm, *Rz* = 0.66 μm), as observed in **Figure 6(b)**. Finally, after 37 h polishing, the cutting grooves were no longer observed, as shown in **Figure 6(b)**, and the surface roughness was *Ra* = 0.01 μm and *Rz* = 0.10 μm.

To examine the precision polished surface more closely and precisely, the precision polished workpiece in **Figure 6(c)** was characterized using an optical surface profiler. The polished surface had an arithmetic mean roughness of *Sa* = 1.8 nm and a maximum height roughness *Sz* = 20.4 nm in the 3D area. The surface roughness in the 2D measurement is *Ra* = 1.7 nm and *Rz* = 9.1 nm, with some small undulations observed. The objective of this study was to achieve a surface

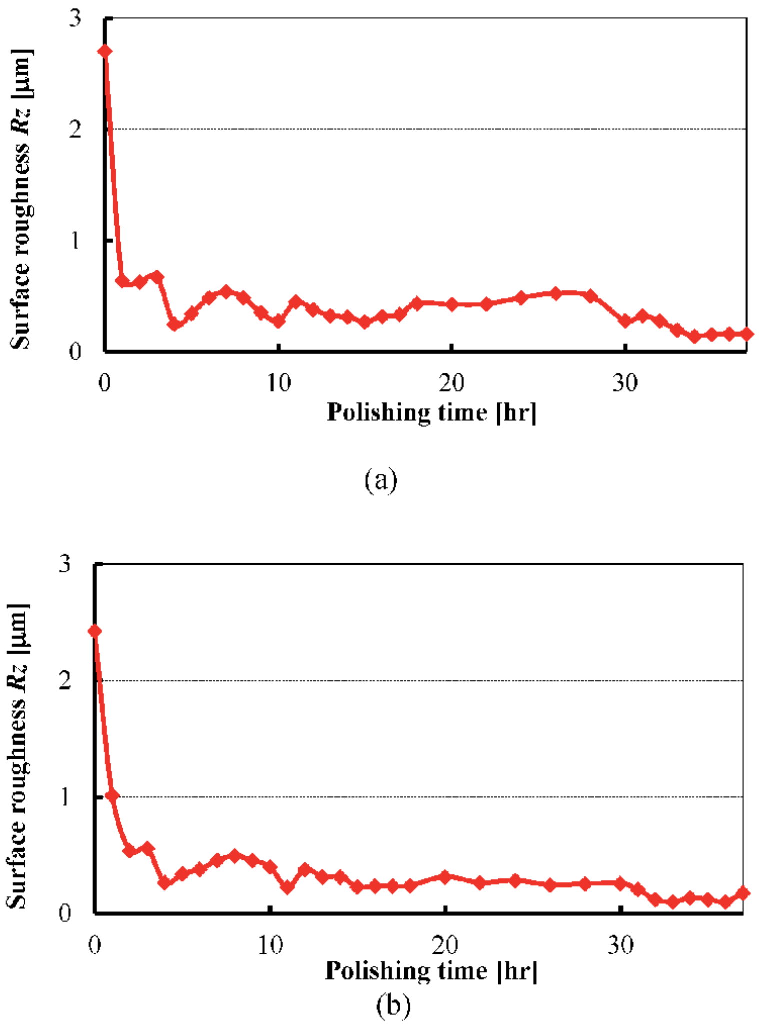


Figure 5.
Surface roughness of polished SUS310S surface. [SUS310S, 0.5%-Al_2O_3 polishing liquid, 1.7 kPa]. (a) inside of workpiece (r = 5 mm). (b) outside of workpiece (r = 20 mm).

roughness of less than *Ra* = 2 nm, which would enable the use of the SUS310S stainless steel molding die.

Our previous polishing experiments on stainless steels with a polishing pressure of 1.7 kPa used SUS310S. Therefore, the SUS304 and SUS310S molding die polishing results are compared for a polishing pressure of 1.2 kPa [12]. The final polished surface roughness was in the same range of *Rz* = 10 nm. The times required to reduce the surface roughness *Rz* from 4 to 1 μm for SUS304 and SUS310S were 7 and 2 h, respectively; for a polishing pressure of 0.7 kPa, these values were 18 and 5 hrs, respectively. These results indicate that the SUS310S molding die may be easier to polish than the SUS304 molding die.

4.3 Designing and manufacturing "centerless polishing machine" for cylindrical molding dies

Figure 7 shows the designed and manufactured centerless polishing machine images to polish cylindrical molding dies. This molding die polishing system will be

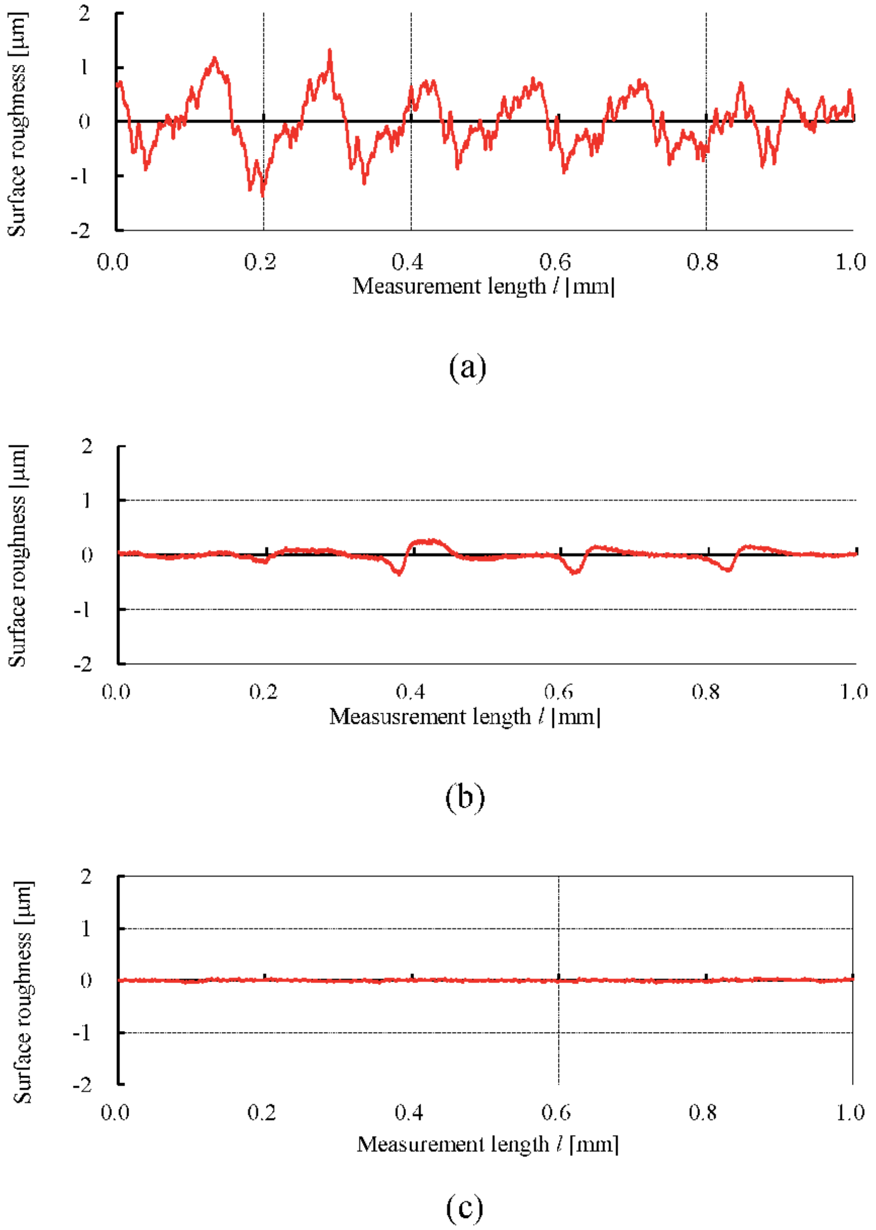


Figure 6.
Surface roughness of polished SUS310S surface. (a) before polishing [Ra = 0.40 μm, Rz = 2.70 μm]. (b) after 1 hour polishing [Ra = 0.07 μm, Rz = 0.66 μm]. (c) after 37 hours polishing [Ra = 0.02 μm, Rz = 0.15 μm].

used for making large scale glass mirrors that are over 600 mm diameter in X-ray telescope field. Therefore large size molding dies have to be manufactured with very small surface roughness. From these background, "centerless polishing machine" was designed. The direction of set-up and polishing of workpieces are lateral direction as shown in **Figure 7(a)**, because it is easy to support and rotate without center fix system of heavy workpieces. In addition, to polish cylindrical molding die surface, polishing pressure that shown in follow polishing examinations for edge surface acts uniformly by using polishing parts self-weight and gravity as shown in **Figure 7(b)**. In these images, a workpiece size is 50 mm diameter and 60 mm length, however the

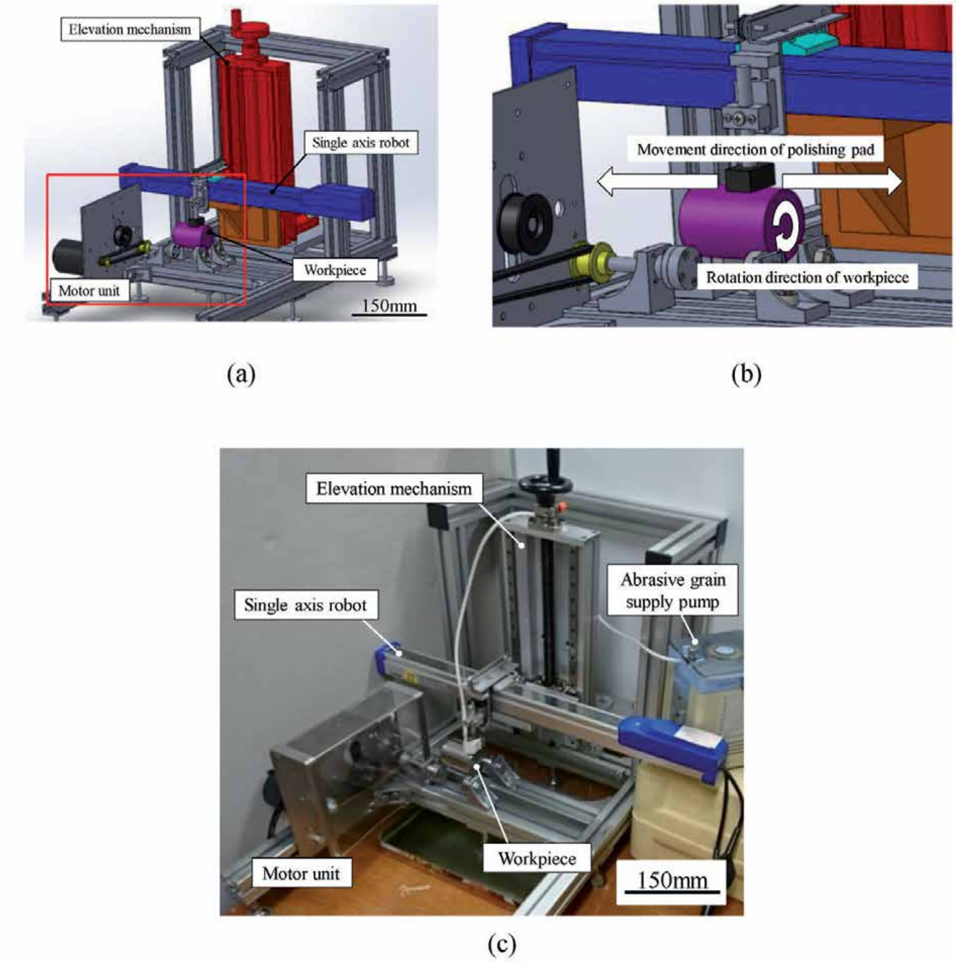


Figure 7.
Centerless polishing machine to polish cylindrical SUS310 molding die surfaces. (a) 3D model of Centerless polishing machine. (b) Polishng method on the machine. (c) Overview of Centerless polishing machine.

designed maximum size for this machine is 200 mm diameter and 200 mm length. By using lifting system and 1 axis robot set up at behind and upside of workpieces, height of polishing parts are able to adjust for each size molding dies.

The centerless polishing machine was manufactured with aluminum pipe frames, as shown in **Figure 7(c)**. Sizes of this machine are 700 x 450 x 500 mm, workpiece rotary drive motor is designed for over 25 kg weight workpieces. The SUS310S molding dies of 50 mm diameter used in slumping process were manufactured by this machine.

5. Glass forming process with “slumping method”

5.1 Effect of molding die surface roughness on formed glass plate surface

A polished SUS310S precision molding die surface with nanoscale surface roughness cannot be easily obtained. Understanding the relationship between the surface roughness of molding dies and formed glass plates will be effective for cost reduction and manufacturing time reduction. In our previous research, the surface roughness of formed glass plates was smaller than that of the polished molding die surface. Therefore, in this work, the effect of the molding die surface on the glass plate surface formed using the slumping process was investigated.

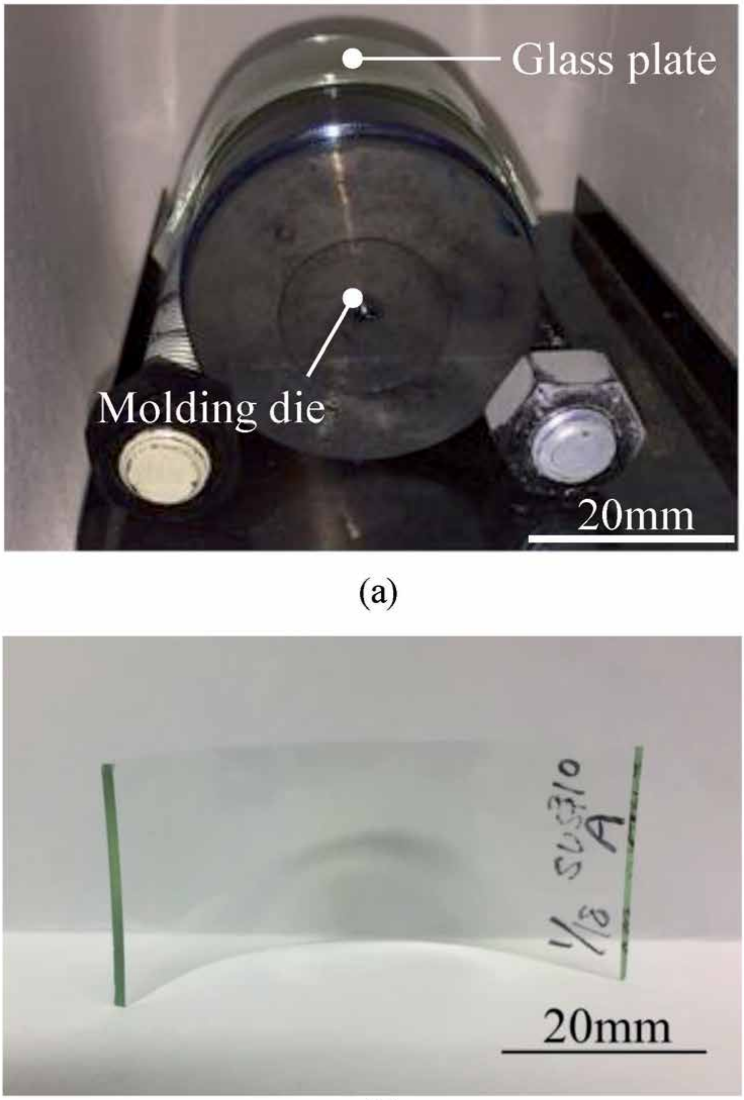
The slumping process was used to form a glass plate using polished SUS310S molding dies with surface roughness of 0.28, 0.13, 0.10, and 0.08 µm. The experimental conditions for the glass forming process were as follows:

1. Glass plate: Soda-lime glass (20 mm x 50 mm x t 2 mm)

2. Furnace: Small type electric furnace (NHK120-H)

3. Temperature: 670°C (Softening temperature of glass)

4. Heating time: 120 min.



(a)

(b)

Figure 8.
Slumping method with SUS310S molding die for glass. [NHK120-H, 120 min at 670°C in electric furnace]. (a) Overview of glass forming in the electric furnace. (b) Formed glass plate with SUS310S molding die.

Figure 8 presents an overview of the glass-forming process in the electric furnace and shows a formed glass plate prepared using the slumping method. As observed in **Figure 8(a)**, one glass plate was placed on a polished molding die surface and then heated to 670°C for 120 min in an electric furnace. The glass plate must be released from the molding die surface with enough cooling time to prevent breakout caused by rapid cooling, as shown in **Figure 8(b)**.

Figure 9 shows the relationship between the surface roughness of the polished molding die surface and that of the formed glass plate prepared using the slumping method. The surface roughness of the molding dies heated in the electric furnace to form glass plates changed to *Ra* of 0.26, 0.14, 0.11, and 0.13 μm, respectively. After the slumping process, the surfaces of the SUS310S molding die were heated at 670°C, and the metallic mirror surface changed to a blue–black surface, as shown in **Figure 10**. The surface roughness of the glass plate before heating was approximately 0.02 μm in *Ra*; this glass plate had a very smooth surface even though it is a commercial product. The surface roughness before and after heating of the glass plates was almost the same (0.02, 0.02, 0.03, and 0.04 μm in *Ra*, respectively). Each glass plate could be molded by the molding dies with different surface roughness, as

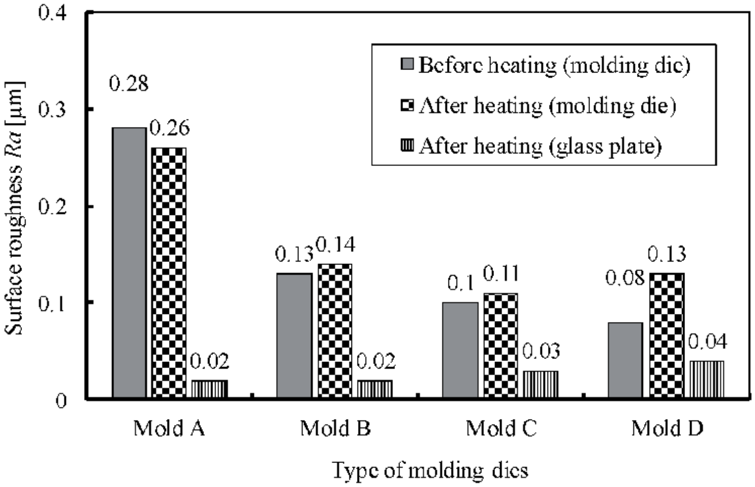


Figure 9.
Relationship between molding die surface and formed glass plate surface with slumping method. [NHK120-H, 120 min at 670°C in electric furnace].

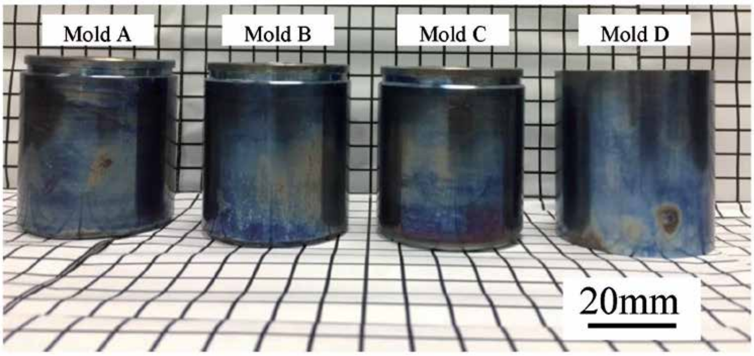


Figure 10.
Used molding die surface at slumping method process. [NHK120-H, 120 min at 670°C in electric furnace].

shown in **Figure 9**. These results indicate that the surface roughness of the molding die had a minor effect on the surface of the formed glass plates.

Generally, it is thought that the surface roughness of manufactured products cannot be smaller than the surface roughness of the molding dies. This principle is applied in molding technology in which melted materials are injected into molding dies. However, in the slumping method, a softened glass plate just remolds along the molding die shape. Therefore, it is thought that the surface roughness of the glass plate is not affected by the roughness of the molding die.

5.2 Analysis of surface roughness copying mechanism

Figure 11 shows schematic view of "slumping method" mechanisms and problems for formed glass plates. The set-up of this process is shown in **Figure 11(a)**, polished molding die have some surface roughness and glass plate of before forming has very smooth surface roughness that is below Rz = 10 nm [13]. Glass plate transforms along molding die surface shape by heating at softening temperature. Then transformation of glass plate occurs by only self-weight in this method.

The glass plate deforms at softening temperature, therefore that surface roughness is keep before smooth roughness at a center of deformed glass plate, as shown

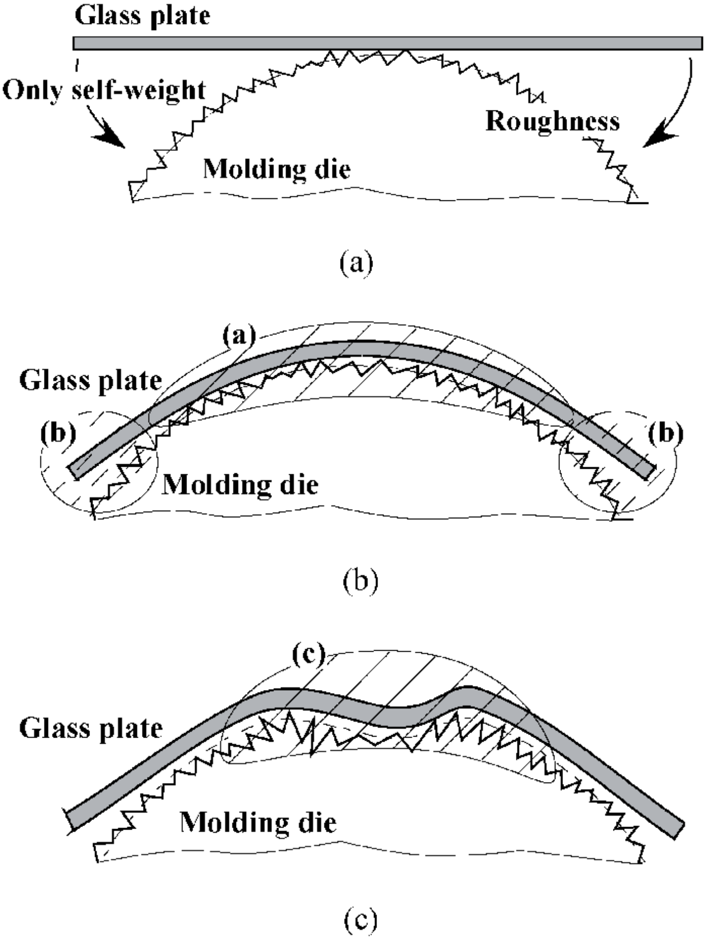


Figure 11.
Schematic of "slumping method" mechanisms and problems for formed glass plates. (a) Set up of slumping method. (b) Analysis of glass forming phenomenon. (c) Effect of molding die shape error for formed glass plate.

in (a) area of **Figure 11(b)**. On the other hand, edge areas of glass plate do not transform along molding die surface shape, because self-weight of glass plate is small in that area as shown in (b) area of **Figure 11(b)** [19, 20]. In this research, real formed glass plate edge areas are almost straight like as a before forming glass plate edge, though that shape is not measured actually.

It was found that the influence of surface roughness of molding die for formed glass plate is considerably small in "slumping method" of this research. However, if molding dies have shape errors, glass plates transform along molding die shape with its errors, as shown in (c) area of **Figure 11(c)**. In this method, shape errors of molding die greatly affects to shape errors of formed glass plate [21–23]. The shape errors and edge transformation of glass plate will be examined as the future works.

6. Discussions

In these trials of molding dies and glass product manufacturing, we were able to obtain research results for a specific aerospace field. The surface roughness of polished molding dies accuracy is below 0.02 μm in *Ra*, if the required accuracy is more than it, this polishing techniques for stainless steels will be used in other manufacturing fields. On the other hand, the surface roughness accuracy of formed glass plates is kept with original glass plate one. This result means that the surface roughness accuracy of the formed glass plate does not depend on the surface accuracy of the base molding die, so it is expected to be a useful result in the conventional manufacturing of optical products.

In recent, molding dies with high precision surface roughness and very small shape error are required in real glass product, such as super mirrors used in X-ray telescopes. If we consider that these techniques will become a molding dies and glass products manufacturing method, the manufacturing cost and manufacturing period of optical products will be shortened, and continuous manufacturing efficiency can be expected in the future. However, optical components used in aerospace field are one of kinds of items and are not produced in large quantities and continuously. When this technology is applied as a manufacturing technology for other products, it will be useful in the industrial field not only as a specific manufacturing technology but also as a sustainable manufacturing technology.

7. Conclusions

In this research, SUS310S precision polishing technology was investigated. The polishing pressure, polishing time, and surface roughness were changed and measured. The following conclusions can be drawn:

1. The precision polishing process transformed the surface of a stainless-steel SUS310S molding die from a surface with many cutting grooves to a finished mirror surface.

2. During the initial polishing process, the surface with a surface roughness of Rz = 2,700 nm was rapidly polished to achieve a surface roughness of approximately 500 nm after less than 5 h. The finished surface roughness after 37 hrs of precision polishing became Ra = 1.7 nm and Rz = 9.1 nm.

3. The precision polishing efficiency was improved by increasing the polishing pressure from 0.7 to 1.7 kPa. The polishing time required to achieve a surface

roughness of *Rz* = 0.5 μm was reduced from 10 to 4 hrs for the SUS310S polishing process.

4. The centerless polishing machine was designed and manufactured to polish cylindrical molding dies. By using this machine, SUS310S molding die surfaces are polished, then it could be used to form glass plates in slumping method.

5. In the slumping process with the polished SUS310S molding die, the surface roughness of the polished molding die was observed to have a minor effect on the surface roughness of the formed glass plates. However, the surface color of the used SUS310S molding die changed from a metallic mirror surface to blue–black after heating at 670°C. This result indicates that the re-polishing process of the heated molding die must be considered when it is used as a slumping molding die again.

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Chapter 3

Life Cycle Assessment of Ordinary Portland Cement (OPC) Using both Problem Oriented (Midpoint) Approach and Damage Oriented Approach (Endpoint)

Busola D. Olagunju and Oludolapo A. Olanrewaju

Abstract

The concern for environmental related impacts of the cement industry is fast growing in recent times. The industry is challenged with high environmental impact which spans through the entire production process. Life cycle assessment (LCA) evaluates the environmental impact of product or process throughout the cycle of production. This can be done using either or both midpoint (process-oriented) and endpoint (damage-oriented) approaches of life cycle impact assessment (LCIA). This study assessed the environmental impact of 1 kg Ordinary Portland Cement (OPC) using both approaches of LCIA. This analysis was carried out using a data modeled after the rest of the world other than China, India, Europe, US and Switzerland. The dataset was taken from Ecoinvent database incorporated in the SimaPro 9.0.49 software. The result of the analysis showed that clinker production phase produced the highest impact and CO2 is the highest pollutant emitter at both endpoint and midpoint approaches. This is responsible for global warming known to affect both human health and the ecosystem. Also, toxicity in form of emission of high copper affects the ecosystem as well as humans. In addition, high fossil resources (crude oil) are consumed and pose the possibility for scarcity.

Keywords: Ordinary Portland cement (OPC), Environmental impact, LCA, LCIA, Midpoint, End point

1. Introduction

With the continuous change in globalization, urbanization, and increase in population, people migrate from one region to another for a better quality of life. This in turn leads to increase in population in such regions. Therefore, there is need to make provisions for infrastructures that will support this increase. The construction industry provides the necessary structure and infrastructure needed for a sustainable environment. However, this sector is faced with different environmental impacts throughout its production cycle. Concrete is one of the important materials in the construction Industry. The production of concrete is required to build the global landscape and accommodate the continuous urbanization as a result of population growth. Recently, construction sector has been recorded to produce large environmental impact which is of continuous concern to the society [1–4]. Ordinary Portland Cement (OPC) is the major constituent of concrete production. Several environmental impacts such as intensive resource and energy consumption are associated with the production of cement [5–9]. This continuous increase in the environmental impacts of the cement industry at the global level is beckoning for attention because of the possible consequences that can succeed these impacts of great concern.

The OPC consists majorly of calcium silicate minerals (limestone, sand and clay) which are extracted and thereafter transferred to the manufacturing plant where they are crushed and finally pulverized into the required texture. This is preheated and eventually transferred into a large kiln of over 1400°C for further treatment to produce the clinker [2, 10]. The clinker is allowed to cool while the heat is trapped back to the preheater unit and gypsum is added to the cooled clinker to control the setting time of the OPC produced. Clinker production is the most energy consuming of all the production stages as enormous source of fuel and electricity is needed [11, 12]. As a result, cement industry is accountable for about 12-15% of industrial energy use [13–15]. Also, about 5-7% of global CO_2 emission is produced during cement production [16]. About 2.6Gt of CO_2 gas emission was recorded from production of cement in 2011, whereby the emission was from the combustion of fossil fuels and the thermal decomposition of limestone (calcination) [17, 18]. International Energy Agency's (IEA) Greenhouse Gas R&D Programme recorded that over 800 g of CO_2 is emitted for every 1000 g of cement produced [19, 20]. Approximately 1 ton of concrete is needed annually by every individual, this makes cement an essential material which requires continuous production [5, 21, 22]. There is a need to quantify the environmental impact of the global production of cement production; the consequent effect on human health, resources and the environment as a whole; and production phases that cause the impacts so that proper recommendation and mitigation strategies can be presented. Studies have shown that the clinker production phase has the highest impact and CO2 is one of the most emitted gases [1, 8, 12, 23]. Recommendation on mitigation strategies varying from partial replacement of clinker, to use of alternative fuel etc. were given. Also, incorporation of best available techniques (BAT) to the production processes were part of the recommendations given [1, 24, 25].

Life cycle assessment (LCA) is a system-oriented tool used for the evaluation and assessment of a product's or process' environmental impacts by analyzing the entire stages of a production process beginning from resource extraction ("cradle") and continues through cement production, to cement applications like concrete structures, their use, and end-of-life (grave) [26]. This brings about the other name known as "cradle to grave". LCA gives a holistic view of the entire production process. According to International Standard Organization (ISO) 14040, the four stages of LCA are represented in **Figure 1** [28, 29].

- Goal and scope describe the assessment objectives alongside with the system of the product and/or process, functional unit, target audience, system boundaries, assumptions etc. It basically defines the jurisdiction of the assumption [30]. The functional unit that will be adopted in this study is 1kilogram of cement. All dataset, analysis and interpretation will take into account this functional unit. This study aims to analyze the environmental impact of 1 kg of cement using midpoint and endpoint LCIA approaches so as to rightly quantify the level of impact and make proper recommendation. The study will be conducted from cradle to gate i.e., from extraction to the production of cement. All data or information with respect to administration in

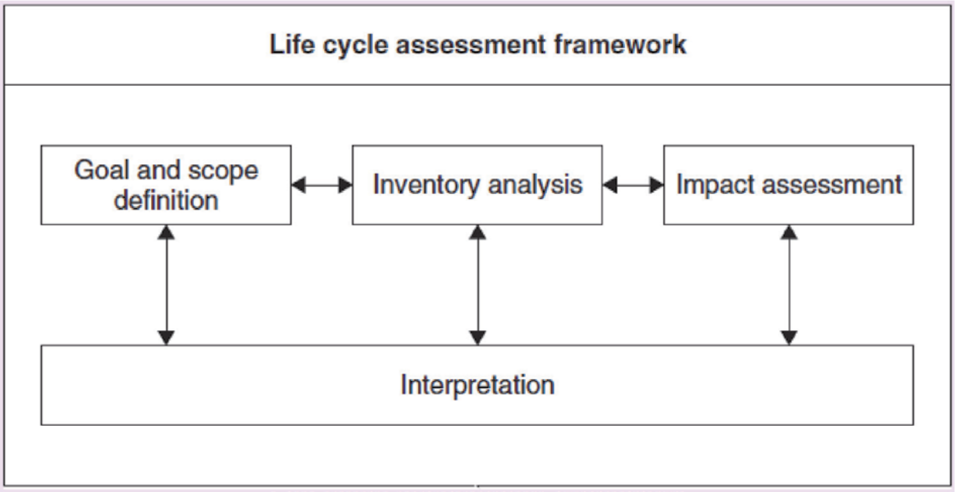

Figure 1.
Stages of LCA [27].

the plant, packaging processes and disposal will not be incorporated into the analysis.

- Life Cycle Inventory (LCI) stage has to do with the compilation of input and output inventory data that are not only consistent with the product under assessment but equally have several environmental coverages. The database of environmental impacts includes all emissions as a result of the production process. In this study, data modeled after the rest of the world apart from China, India, Europe, US and Switzerland will be considered. Dataset will be taken from Ecoinvent dataset; one of the highly recommended database company [31] which was recently considered to be one of the best database for construction materials [32].

- Life cycle impact assessment (LCIA) is a multiple-issue tool used to evaluate potential environmental impacts that are in-line with environmental resources identified in the life cycle inventory. This assessment addresses several environmental issues such as energy, climate change, water pollution, etc., thus allowing for comprehensive evaluation of the impacts of the product [27]. The LCIA stage is a multifaceted process which groups all inventory into their various impact categories, thereafter analysis is conducted at the final stage where LCIA and LCI results are interpreted.

- Interpretation which is the last stage is an efficient method used to evaluate, compute and categorize the result from the information provided by LCI and LCIA and relate them effectively by showing the effect each output data has on each impact categories and consequently establishing the goal of the study [33]. In this phase, production processes and substance with significant impacts will be presented in a comprehensive and lucid manner after which proper recommendation are made.

Several studies have been carried out with respect to life cycle assessment of the cement industry to evaluate the impact of its production processes [2, 21, 34–36].

Often times, these studies are modeled after a country, or particular cement plant in a certain place. Rarely do we find LCA study modeled after the world. Also, more studies are more focused on using the midpoint approach only. This study will therefore carry out a life cycle assessment modeled after the rest of the world other than from China, India, Europe, US and Switzerland using both endpoint and midpoint approaches to analyze the environmental impact of OPC production. The remainder of this article is divided into method under section two, results under section three, discussion under section four and the last section concludes.

2. Method

LCA is an assessment tool for analyzing the environmental implication of process or product by taking cognizance of the potential effect of the entire cycle chain of such process or product. One good posture LCA takes in a system study is to give holistic LCIA method and its calculations (environmental impacts) are based on definite factors. This helps to speed up the analysis as well as simplify the system studied.

There are two approaches in LCIA: process-oriented approach (midpoints) and damage-oriented approach (endpoints). The life cycle assessment expert can use either of them for evaluation [37]. Midpoints and endpoints are characterization models that indicate effects at different levels. In the midpoint approach, flows are categorized into environmental impacts to which they contribute. This approach contains about 18 impact categories: global warming, stratospheric ozone depletion, ionizing radiation, ozone formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity etc. [38]. This approach helps to simplify numerous flows by streamlining them into few prevalent environmental impacts. Endpoint approach on the other hand classifies impacts into 22 environmental impact categories and thereafter simplifies flow to evaluate impacts at the area of significance to life (AoSL): human health, ecosystem, resources [39]. Although, the midpoint approach gives a cause-effect evaluation right from the emission of substance or usage of resources, endpoint helps to answer the question: why should I worry about these impacts? [40].

ReCiPe, an acronym for the developers: RIVM, Radboud University, CML and PRé Consultants, is the LCIA method that will be adopted in this study; it offers the platform for carrying LCIA using both approaches [37]. The development of ReCiPe was mainly as a result of the need to harmonize the midpoint and endpoint methods and consequently break the barrier of the selection of LCIA method in LCA model [38].

When midpoint LCIA method is used for analysis, the result presents 18 impact categories, which covers several impacts while endpoint on the other hand presents the 22 impact categories. These impacts are later classified in three damage categories in the AoSL which are human health, resources and ecosystem based on their effects; giving a slightly easy result analysis. In human health category, ReCiPe uses the disability-adjusted life years (DALY) which means the years of life expended or the years of damage to life as a result of environmental impacts. Ecosystem damage category is measured by species/yr.; this denotes species lost in a year due to emissions to the environment, water body, etc. and the resources damage is based on economic loss due to marginal increase in costs as a result of scarcity emerging from resource extraction. It is measured using USD (2013) [38, 41, 42].

ReCiPe uses a cultural theory as 3 models are used to qualify 3 basic assumptions and consideration [43]. These are the Individualist (I), the Egalitarian (E) and Hierarchism (H). The Individualist (I) considers the short-range impact because of the greatest significant chemicals. Egalitarian (E) is established on preventive measure that takes into consideration the long-term perception and implied risk.

Hierarchism (H) on the other hand is a balanced perspective whose basis is on the prevalent policy principles [44]. Also, ReCiPe provides other set of weighting factors (A) by averaging the weighting factors of the three viewpoints. The balanced term H is the default, recommended choice. The average value (A) will be adopted in this study. Therefore, ReCiPe Midpoint (H)- World H and ReCiPe Endpoint (H)-World H/A, are used in this study for the assessment of ordinary Portland cement. The software used for the LCA in this study is SimaPro 9.0.49 which incorporates the latest version of Ecoinvent (v 3.5) database [45].

The dataset in **Table 1** describes the production of clinker; in the production, different types of alternative fuels and raw materials are used. This database is

Inputs from Technosphere	**Amount**
Ammonia, liquid	0.000918 kg
Bauxite	0.000148 kg
Calcareous marl	0.459 kg
Cement factory	6.2e-12 unit
Clay	0.326 kg
Diesel, burned in building machine	0.0132 MJ
Diesel, low-sulfur	5.61e-06 kg
Electricity, medium voltage	0.0593 kWh
Hard coal	0.0362 kg
Heavy fuel oil	0.0249 kg
Industrial machine, heavy, unspecified	3.76e-05 kg
Iron ore, crude ore, 46% Fe	0.000143 kg
Light fuel oil	0.000367 kg
Lime	0.821 kg
Hydrated, lose weight	0.00388 kg
Limestone, crushed, for mill	0.0308 kg
Liquefied petroleum gas	6.68e-07 kg
Lubricating oil	4.71e-05 kg
Meat and bone meal	0.00948 kg
Natural gas, high pressure	0.000206 m^3
Petrol, unleaded	2.54e-07 kg
Petroleum coke	0.00442 kg
Pulverized lignite	0.00167 MJ
Refractory, basic, packed	0.00019 kg
Refractory, fireclay, packed	8.21e-05 kg
Refractory, high aluminum oxide, packed	0.000137 kg
Sand	0.0103 kg
Steel, chromium steel 18/8, hot rolled	5.86e-05 kg
Tap water	0.336 kg
Urea, as N	1.5e-06 kg
Transport, freight, lorry	0.05tkm

Inputs from Technosphere, wastes	**Amount**
Inert waste, for final disposal	−0.000179 kg
Municipal solid waste	−4.45e-05 kg
Inputs from environment	**Amount**
Water, cooling, unspecified natural origin	9.57e-06 m3
Water, unspecified natural origin	0.0016 m3
Emissions to air	**Amount**
Acenaphthylene	2.68e-10 kg
Ammonia	2.25e-05 kg
Antimony	2.24e-09 kg
Arsenic	1.22e-08 kg
Benz(a)anthracene	5.18e-12 kg
Benzene, hexachloro-	2.59e-12 kg
Benzo(a)pyrene	2.08e-12 kg
Benzo(b)fluoranthene	6.12e-12 kg
Benzo(ghi)perylene	3.77e-13 kg
Benzo(k)fluoranthene	4.43e-12 kg
Beryllium	2.97e-09 kg
Cadmium	6.87e-09 kg
Carbon dioxide, fossil	0.838 kg
Carbon dioxide, non-fossil	0.0155 kg
Carbon monoxide, fossil	0.000489 kg
Chromium	2.1e-09 kg
Chromium VI	5.44e-10 kg
Chrysene	5.65e-13 kg
Cobalt	3.98e-09 kg
Copper	1.42e-08 kg
Dibenz(a,h)anthracene	2.88e-12 kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	9.43e-13 kg
Fluoranthene	4.72e-11 kg
Fluorene	4.28e-11 kg
Hydrogen chloride	6.63e-06 kg
Indeno(1,2,3-cd)pyrene	1.13e-12 kg
Lead	8.39e-08 kg
Manganese	5.74e-10 kg
Mercury	3.25e-08 kg
Methane, dichloro-, HCC-30	5.18e-08 kg
Methane, fossil	8.79e-06 kg
NMVOC, non-methane volatile organic compounds.	5.59e-05 kg
Nickel	6.71e-09 kg
Nitrogen oxides	0.00109 kg

Emissions to air	**Amount**
PAH, polycyclic aromatic hydrocarbons	1.27e-12 kg
Particulates, > 10 um	2.37e-05 kg
Particulates, < 2.5 um	6.5e-06 kg
Particulates, > 2.5 um, and < 10um	7.86e-06 kg
Phenanthrene	6.6e-10 kg
Phosphorus	3.48e-13 kg
Pyrene	3.44e-11 kg
Selenium	1.98e-09 kg
Sulfur dioxide	0.000392 kg
Thallium	1.3e-08 kg
Tin	9.05e-09 kg
Vanadium	4.97e-09 kg
Water	0.000294 m3
Zinc	6.34e-08 kg
Emissions to water	**Amount**
Arsenic, ion	1.29e-10 kg
Cadmium, ion	2.59e-11 kg
Chromium, ion	5.18e-11 kg
Copper, ion	2.59e-11 kg
Lead	2.72e-11 kg
Mercury	2.72e-13 kg
Nickel, ion	2.59e-11 kg
Phosphorus	7.77e-11 kg
Water	0.00165 m3
Zinc, ion	5.18e-11 kg
Output to Technosphere: waste and emissions to treatment	**Amount**
Inert waste, for final disposal	0.0001787 kg
Municipal solid waste	1.9013E-7 kg

Table 1.
Production data of 1 kg of clinker.

modeled for the world without Europe, US, Switzerland, China, India and it is valid from 2005 to 2018.

This dataset was created as a weighted average of the regional clinker production activities. The activities end with the cooling of the produced clinker. It includes the whole manufacturing process to produce clinker (raw material provision, grinding and mixing; rotary kiln process), internal processes (transport, etc.) and for the infrastructure only the rotary kiln (material consumption) is taken into account [46]. No administration is included. Waste (as secondary fuel and raw material) enter the system without environmental burdens from upstream processes. After the production of clinker, cement was thereafter produced. **Table 2** represents the production data of 1 kg of cement [47].

Inputs from Technosphere	**Amount**
Cement factory	5.36e-11 unit
Clinker	0.902 kg
Electricity, medium voltage	0.0376 kWh
Ethylene glycol	0.00019 kg
Gypsum, mineral	0.0475 kg
Limestone, crushed, for mill	0.05 kg
Steel, low-alloyed	0.00011 kg
Emissions to air	**Amount**
Heat, waste	0.135 MJ

Table 2.
Production data of 1 kg of Portland cement.

3. Results

3.1 Midpoint (process-oriented) approach

The midpoint approach presents the results of the impact categories in 2 tiers i.e., characterization and normalization. Normalization is based on the normalization factor which is the annual percentage of damage per capital which is the combination of different impact categories. The normalization factor is highly subjective and often set by method or software producers. Therefore, only characterization will be analyzed in details in this study to reduce uncertainties and also for proper understanding.

Table 3 gives a better insight as the values are given based on the amount of impact for every 1 kg of OPC produced. Environmental impacts are categorized into 18 categories based on their contribution as seen. As said above, different impact categories have their own equivalence (units). The Global warming, terrestrial ecotoxicity and resource scarcity are the impact categories with the highest impacts. These Impact hotspots will further be analyzed to know the production process and substance causing these emissions and bringing about these environmental consequences.

Global warming brings about climate change which affects both human health and species. **Table 3** shows that for every 1 kg of OPC produced, 0.911 kg of CO_2 equivalent is emitted during the production process. This implies that there is a very high tendency of global warming when cement as low as 1 kg is produced as a result of enormous CO_2 that is emitted. This result is further analyzed to know the production process and substances causing this emission. Specification to process gives us information about the particular production process that contributes to the impact category and specification to substance gives the particular substance that is emitted or that affects the impact category. **Tables 4** and **5** show the specification to substance and specification to process respectively. While the former gives insight to the particular amount of CO_2 emitted and the CO_2 equivalent, the latter shows the particular production process that produces these emissions.

Table 4 shows that 97.1% of CO_2 is produced while less than 3% are other gases. **Table 5** shows that 85.6% of 97.1% CO_2 seen as in **Table 2** was produced during clinker production phase of 1 kg of OPC that was produced. The specification to process of global warming in **Table 6** shows that 83.2% of clinker production brings about global warming.

S/N	Impact category	Unit	Portland cement
1	Global warming	kg CO_2 eq	0.911
2	Stratospheric ozone depletion	kg CFC 11 eq	7.84E-8
3	Ionization radiation	kBq Co-60 eq	0.00127
4	Ozone formation, Human health	kg NOx eq	0.00145
5	Fine particulate matter formation	kg PM2.5 eq	0.000577
6	Ozone formation, Terrestrial ecosystem	kg NOx eq	0.00147
7	Terrestrial acidification	kg SO_2 eq	0.0014
8	Freshwater eutrophication	kg P eq	1.16E-5
9	Marine eutrophication	kg N eq	3.56E-7
10	Terrestrial ecotoxicity	kg 1,4-DCB	0.438
11	Freshwater ecotoxicity	kg 1,4-DCB	9.92E-5
12	Marine ecotoxicity	kg 1,4-DCB	0.000383
13	Human carcinogenic toxicity	kg 1,4-DCB	0.00121
14	Human non-carcinogenic toxicity	kg 1,4-DCB	0.0153
15	Land use	m2a crop eq	0.00365
16	Mineral resources scarcity	kg CU eq	0.00464
17	Fossil resources scarcity	kg oil eq	0.0784
18	Water consumption	m^3	0.00185

Table 3.
Impact assessment table of 1 kg Portland cement using midpoint LCIA method.

S/N	Substance	Portland cement (%)
	Total of all compartment	100
	Remaining substances	0.102
1	Carbon dioxide, fossil	97.1
2	Methane, fossil	2.61
3	Dinitrogen monoxide	0.156

Table 4.
Specification to substance of global warming.

S/N	Process	Portland cement (%)
	Total of all processes	100
	Remaining processes	2.8
1	Clinker production	85.6
2	Diesel, Burned in building machine	2.8
3	Electricity high voltage	6.7
4	Heat	2.11

Table 5.
Specification to process of carbon dioxide (fossil) in global warming.

S/N	Substance	Portland cement (%)
	Total of all processes	100
	Remaining processes	15.23
1	Clinker production	83.2
2	Diesel, Burned in building machine	0.519
3	Electricity high voltage	0.418
4	Heat	1.41

Table 6.
Specification to process of global warming.

S/N	Substance	Cement portland (%)
	Total of all compartments	100
	Remaining substances	0.083
1	Beryllium	0.22
2	Cadmium	1.06
3	Chromium	0.208
4	Cobalt	0.149
5	Copper	61.5
6	Lead	2.56
7	Mercury	11
8	Nickel	7.53
9	Selenium	0.34
10	Thallium	0.158
11	Tin	0.301
12	Vanadium	7.06
13	Zinc	7.77

Table 7.
Specification to substance of terrestrial ecotoxicity.

Terrestrial ecotoxicity affects terrestrial species and it is measured by the quantity of 1,4-dichlorobenzene (DCB) produced. **Table 1** shows that for every 1 kg of OPC produced, 0.4381 kg of 1,4 DCB equivalent is produced to the terrestrial body. The specification to substance of terrestrial ecotoxicity that contributed to the overall amount of DCB with 61.5% of copper is shown in **Table 7**. The rest of the percentage comes from heat/power generation, ammonia emission, break wear emissions, electricity and some other with minimal emissions. **Table 8** shows the contribution of different stages of production with copper having the highest percentage of 38.72% while Clinker and brake wear emissions, lorry are 16.6% and 16.47% respectively. The rest of the percentage comes from heat/power generation, ammonia emission, electricity and some other with minimal emissions.

Fossil resource scarcity results to unavailability of fuel resources such as oil, gas and coal energy. It thereby increases the cost of available ones. It is measured by the quantity of oil produced per 1 kg of OPC produced. **Table 9** shows that crude oil (43.7%), coal (43.2%) and natural gas (13.1%) are substances that are used up

S/N	Process	Cement portland (%)
	Total of all compartments	100
	Remaining processes	9.74
1	Ammonia, liquid	0.949
2	Brake wear emissions, lorry	16.47
3	Clinker	16.6
4	Copper	38.72
5	Diesel burned in building machine	0.742
6	Electricity (high voltage)	2.093
7	Ferronickel, 25% Ni	2.92
8	Heat	2.482
9	Heavy fuel oil	1.44
10	Zinc	1.13

Table 8.
Specification to process of terrestrial ecotoxicity.

S/N	Substance	Portland cement (%)
	Total of all compartments	100
1	Coal	43.21
2	Gas, natural/m3	13.1
3	Oil, crude	43.7
4	Peat	0.00681

Table 9.
Specification to substance of fossil resource scarcity.

S/N	Process	Cement portland (%)
	Total of all processes	100
	Remaining processes	11.6
1	Hard coal	37.01
2	Lignite	1.6
3	Natural gas	8.22
4	Petroleum	41.57

Table 10.
Specification by process of fossil resource scarcity.

which eventually result into scarcity. **Table 10** shows almost the same result with 41.57% Petroleum, Coal 37% and Natural gas 8.22%.

3.2 Endpoint (damage oriented) approach

This approach presents several impact categories which is further classified into their various damage categories. The analysis in this approach is majorly on the

AoSL (damage category). It also shows impacts at different categories but eliminates other aspects without the knowledge of emission factors [37]. **Table 11** give the characterization result of the analysis of 1 kg of OPC. This presents 22 environmental impact categories with three specific damage units based on their effects.

The characterization result of the impact assessment represented in **Table 11** gives insight into each of the impacts in the damage category with the individual units of the impact showing what is affected. With their units in view, these impact categories were thereafter classified into their damage categories. This is represented in **Table 12**.

The damage assessment as shown in **Table 12** gives a summary of the damage category each of the impact categories in the characterization falls under, which are

S/N	Impact category	Unit	Portland cement
1.	Global warming, Human health	DALY	8.45E-7
2.	Stratospheric ozone depletion	DALY	4.16E-11
3.	Ionizing radiation	DALY	1.08E-11
4.	Ozone formation Human health	DALY	1.32E-9
5.	Water consumption Human health	DALY	2.69E-9
6.	Fine particulate Formation	DALY	3.62E-7
7.	Human carcinogenic toxicity	DALY	4.02E-9
8.	Human non-carcinogenic toxicity	DALY	3.49E-9
9.	Global warming, Terrestrial ecosystems	Species/yr	2.55E-9
10.	Global warming, Freshwater ecosystems	Species/yr	6.97E-14
11.	Ozone formation Terrestrial ecosystems	Species/yr	1.89E-10
12.	Terrestrial acidification	Species/yr	2.96E-10
13.	Freshwater Eutrophication	Species/yr	7.74E-12
14.	Marine Eutrophication	Species/yr	6.05E-16
15.	Terrestrial ecotoxicity	Species/yr	4.99E-12
16.	Freshwater ecotoxicity	Species/yr	6.88E-14
17.	Marine ecotoxicity	Species/yr	4.02E-14
18.	Land use	Species/yr	3.24E-11
19.	Water consumption, Terrestrial ecosystems	Species/yr	1.72E-11
20.	Water consumption, Aquatic ecosystems	Species/yr	1.17E-11
21.	Mineral Resource scarcity	USD2013	0.00107
22.	Fuel resource scarcity	USD2013	0.022

Table 11.
Impact assessment of 1 kg Portland cement using endpoint LCIA method.

S/N	Damage category	Unit	Portland cement (%)
1	Human health	DALY	$1.22E^{-6}$
2	Ecosystem	Species/yr	$3.1E^{-9}$
3	Resources	USD2013	0.0231

Table 12.
Damage assessment of 1 kg Portland cement using endpoint LCIA method.

Human health, Ecosystem and Resources. Human health has a value of $1.22E^{-6}$ DALY, Ecosystem of $3.1E^{-9}$ species/yr., Resources of 0.0231 USD 2013.

Thus, further detailed analysis was carried out on the damage assessment. The specification to process of human health as shown in **Table 13** reveals that 70.1% of the damage caused on human health is from the clinker production process. Others are from energy generation: diesel (4.02%), electricity (11.1%), hard coal (4.9%), heat (4.5%) and transportation (1%). This is as a result of the emission of primary gases such as CO_2, SO_2, NO_2, particulate matter and water. The specification to substance presented in **Table 14** shows that 67.3% of the damage is as a result of CO_2 emission with other substances such as Nitrogen oxides (8.23%), Sulfur dioxide (12.2%), particulate matter <2.5 μm (9.01%), water (2.5%).

Also, the specification to process of the damage to the ecosystem summarized in **Table 15** opined that 77.8% of the total damage to the ecosystem originates from the clinker production process as observed in the case of human health, a large portion of the remaining percentage is from energy generation (Diesel is 1.81%, electricity 7.7%, hard coal 2.8%, heat 2.6%) during which primary gases (CO_2, SO_2, NO_2) are emitted; 2.2% is from transportation. The Specification to substance analysis of damage to the ecosystem is presented in **Table 16**. CO_2 constitutes the highest emission percentage which is 79.9%, and other substances constitute the rest of the percentages. These other substances are Nitrogen oxides, constituting 9.48%, Sulfur dioxide is 5.6%, methane 2.1%, water 1.2%. These emissions are often emitted into the water body and the environment (air).

Table 17 presents specification to process of damage to resources. This shows that the major resource deletion is from Petroleum (65.8%), natural gas (11.3%),

S/N	Process	Portland cement (%)
	Total of all processes	100
	Remaining processes	4.38
1	Clinker	70.1
2	Diesel burned in building machine	4.02
3	Electricity, high voltage	11.1
4	Hard coal mine operation	4.9
5	Heat, district, or industrial	4.5
6	Transport freight	1

Table 13.
Specification to process of human health.

S/N	Substance	Portland cement (%)
	Total of all compartment	100
	Remaining substances	0.79
1	Carbon dioxide, fossil	67.3
2	Nitrogen Oxides	8.23
3	Particulates, <2.5 μm	9.01
4	Sulfur dioxide	12.2
5	Water	2.5

Table 14.
Specification to substance of human health.

S/N	Process	Portland cement (%)
	Total of all processes	100
	Remaining processes	5.09
1	Clinker	77.8
2	Diesel burned in building machine	1.81
3	Electricity, high voltage	7.7
4	Hard coal mine operation	2.8
5	Heat (Natural gas)	2.6
6	Transport, freight	2.2

Table 15.
Specification to process of ecosystems.

S/N	Substance	Portland cement (%)
	Total of all compartment	100
	Remaining substances	1.72
1	Carbon dioxide, fossil	79.9
2	Nitrogen Oxides	9.48
3	Sulfur dioxide	5.6
4	Methane	2.1
5	Water	1.2

Table 16.
Specification to substance of ecosystems.

S/N	Process	Portland cement (%)
	Total of all processes	100
	Remaining processes	0.6
1	Clay	4.1
2	Hard coal	11.8
3	Natural gas,	16.7
4	Petroleum production, on-shore	66.8

Table 17.
Specification to process of resources.

S/N	Substance	Portland cement (%)
	Total of all compartment	100
	Remaining substances	0.473
1	Clay	4.19
2	Coal, hard	11.4
3	Gas, natural/m^3	16
4	Oil, crude	67.9

Table 18.
Specification to substance of resources.

hard coal (8.8%), clay (4.2%) and the specification to substance; **Table 18** revealed the same substances as well.

4. Discussion

4.1 Midpoint

The characterization result of the midpoint analysis as presented in **Table 3** shows that the impact category: global warming is as a result of 0.911 kg of CO2 eq emitted into the air. The consequential effect of global warming is the change in the climatic conditions. Several studies that have been carried out estimated the impact of climatic changes from the production of cement within the range of 0.628 kg CO2 eq −0.920 kg CO2 eq (though their evaluation was with respect to 1ton of cement proceed) per kg of cement produced [10, 24, 35, 48–52]. Ozone formation, Human health and Ozone formation, Terrestrial ecosystem are as a result of 0.00145 kg NOx eq and 0.00147 respectively per kg of OPC. This impact category is measured with NOx emission into the air and also showed it affects human beings. This is one of the main air pollutants which when react with atmospheric air to produce nitrogen dioxide in which its high concentration in human body when inhaled has both direct and indirect effect on humans. It causes death in species and causes health complication on human. 0.000577 kg PM2.5 eq causes Fine particulate matter formation impact for 1 kg of OPC produced. This means that particulate matter with sizes less than 2.5 micrometer is emitted into air. Due to the small sizes of this particle, they have the ability to go through the nasal cavity of human and affect the lungs and other health issues. This value of fine particulate matter in this study is in line with values in literature within the range of 0.00023–0.0015 kg PM2.5 eq per kg of OPC [36, 52]. The result of terrestrial acidification in this study is 0.0014 SO2 eq and is in line with result of Li et al. (2015) which was in the range 1.144–1.467 kg SO2 eq per kg of OPC [35]. SOx emission is often from the burning of fuel with high Sulfur content and it has high tendency to cause acid rain and other health issues. Emission of 0.00127 kBq Co-60 eq give rise to Ionization radiation. 1 kg of OPC produced emits 0.00127 kilo-Becquerel of Cobalt 60 eq.; this can cause acute radiation, sick burn and even death. **Table 3** also showed that per kg of OPC produced, about 0.455 kg 1,4 DCB eq of different toxicity is emitted in to air and water. 1,4 DCB eq represents 1,4 dichlorobenzene equivalents. This is higher than values found in literature. This might be due to energy sources and fossil fuel mix [48, 53]. High toxicity in the environment (air and waterbodies) have effect on both human and ecosystem. Its health implication is wide-ranging and often times terminal. Pandemic in the aquatic community is often time traced to toxicity. Water consumption during the production of cement is 0.00185 m3: it was found to be comparable with that of Tun et al. and Chen et al. which was within 0.00019-0.00187 m3 [52, 53]. Also 0.0784 kg oil eq of Fossil resources scarcity is expected for every 1 kg of OPC produced. This resonates with the value from the study of [48, 53] with values ranging from 0.07 to 0.234 kg oil eq.; the three impacts categories with high environmental impacts are human health, terrestrial ecotoxicity and Fossil resources scarcity. In order to understand and recognize key factors responsible for these major impact categories, a further contribution analysis was carried out to show that exact substances and process stage contributing to these impacts and their level of contribution.

Global warming impact category results from the emission of 0.911 kg of CO_2 eq as seen in **Table 3**. The exact substances that give rise to 0.911 kg of CO_2 eq is as represented in **Table 4**. As presented in this table, 97.1% of 0.911 is from actual emission of CO2 i.e., 0.885 kg of CO_2 is emitted per kg of OPC produced. The remaining 0.026 kg of CO_2 eq is from the emission of CH_4 and N_2O. These gases (CO_2, CH_4 and N_2O) are major GHGs, though N_2O and CH_4 have high capacities to cause global warming: about 25 and 300 respectively, the larger emission of CO_2 cause explains why it's the major greenhouse gas that give rise to global warming and consequently climatic changes. The production processes in which these emissions are produced are as presented in **Table 5**. 83.2% of 0.911 kg CO_2 eq is from the clinker production phase (both from calcination and burning of fuel) i.e., 0.758 kg of CO_2 eq is produced at the clinker production phase and the remaining 0.153 kg of CO_2 eq is from various energy sources. A further analysis on co2 emission represented in **Table 6** reveals that 85.6% of the total CO2 emitted during the production of 1 kg of cement (0.885 kg) is emitted at the clinker production phase i.e., 0.75.8 kg of CO_2 is emitted at the clinker production stage. Recall that 0.758 kg of CO_2 eq is produced at the clinker production phase. This further analysis therefore shows that 0.76 kg of actual CO_2 emitted per kg of OPC produced is from clinker production stage. These results are comparable with that of most studies though the result of this study is lower that Stanford's result [48]. In this case more emissions of CO_2 are experienced in burning of fuels for the road transportation of clinker. Clinker used for the production of cement in this Brazilian cement plant are imported and on-road transportation being one of the major pollutants and CO_2 emitters, higher carbon footprint from this cement plant is inevitable.

Terrestrial ecotoxicity impact category as presented in **Table 3** is as a result of emission of 0.4381 kg of DCB equivalent which is produced into air. **Tables** 7 and **8** represent further analysis to know the exact substance and production process respectively contributing to this impact. **Table 7** helps us to know that these impacts are as a result of emissions of heavy metals into the air. Copper has the highest value of 61.5% of all these metals and they all have different effects on both human and the ecosystem having established that whatever affects human affects the ecosystem and vice versa. **Table 8** on the other hand showed the production processes in which the emissions are produced. This shows that the raw material extraction stage (copper production), clinker production and the transportation (break wear emission, lorry) have the highest percentage contributions while others are majorly from energy sources and raw material extraction.

Fossil resource scarcity shows results represent the potential lack of scarcity that can be experienced per kilogram of cement produced. From **Table 3**, 0.0784 kg oil eq becomes scarce per kg OPC produced. This because 43.21% of coal, 43.1% of oil, 13.1% of natural gas are burnt during the production of 1 kg of OPC. This is represented in **Table 9**. These substances are used up at the energy generation phase (in this case are hard coal, petroleum, lignite and natural gas) of the cement production process as represented in **Table 10**.

4.2 Endpoint

Endpoint analysis categorizes the numerous impact categories into their damage categories based on the effects caused. This is represented in **Table 11**. Further analysis was carried out to show the exact substances production process stage contributing to these damage categories and their level of contribution. Damage to Human health as represented in **Table 11** has a value of $1.22E^{-6}$ DALY per kg of OPC produced. As seen in the midpoint analysis, clinker production stage has high contribution; in **Table 13**, clinker production contributes immensely to the damage of human health: 70.1% of damage to human health is from the clinker production process, 24.52% is from energy generation (electricity and fossil fuel) and 1% is from transportation. The substances that are emitted in this production process stages that cause this damage is represented in **Table 14**. Again, just as in the midpoint analysis, CO_2 emission has high contribution; 67.3% of CO_2 emission causes damage to human health, other substances are Nitrogen oxides (8.23%), Sulfur dioxide (12.2%), particulate matter <2.5 μm (9.01%), water (2.5%); each of which have respective implications on human health.

Damage to Ecosystem as recorded in **Table 11** has a value of $3.1E^{-9}$ species/yr. per kg of OPC produced. **Tables 15** and **16** show the result of analysis of substance and process responsible for damage to ecosystem respectively. 77.8% of damage to Ecosystem is from the clinker production stage and other production stages are energy generation and transportation. 79.9 of CO2 gas is emitted and thereby cause damage to the ecosystem and other substances such as Nitrogen oxides: 9.48%, Sulfur dioxide 5.6%, methane 2.1% and water 1.2%. Again, this established the fact that whatever will affect ecosystem will affect human health and vice-versa. **Table 11** showed that the potential marginal price increase of Resources per kg of OPC produced is 0.0231 USD (2013). This means that every resource used to produce 1 kg of OPC, poses an increase in the price of those resources by 0.0231 USD (2013). Further analysis to know what these resources are presented in **Table 18** shows that they are crude oil (67.9%), natural gas (16%), hard coal (11.4%) and clay (4.19%). The result of the specification to process represented in **Table 17** shows that about the same percentage amount of the substance is used in the energy generation stage and resource extraction (clay).

The result of the endpoint analysis is comparable with results of literature with CO2 emission and the clinker production stage being the highest contributors [52, 53]. There is variation in the resources of Chen et al. and Tun et al., this is because coal was the major source of fossil fuel for the production of cement.

5. Conclusion

This study carried out a LCA assessment on 1 kg of OPC so as to analyze the environmental impact of cement production using both the midpoint (process-oriented) and endpoint (damage-oriented) approaches. The production process modeled after the rest of the world excluding China, India, Europe, US and Switzerland; therefore, dataset modeled after the world was used to carry out the assessment. This dataset was extracted from Ecoinvent database incorporated in the SimaPro 9.0.49 software was used for this study.

In the midpoint assessment, characterization result showed the impact of 18 impact categories. The top three with highest impacts: global warming (0.911 kg CO2 eq), terrestrial ecotoxicity (0.438 kg 1,4-DCB), and fossil resources scarcity (0.0784 kg oil eq) were further analyzed. Global Warming has the highest environmental impact of 0.911 kg CO2 eq. Global warming is often times a result of high GHG emission and its effect is seen in changes in climatic conditions. Further analysis on this impact category shows 88.5 kg out of 0.911 kg CO2 eq is the actual CO2 gas emitted and 75.6 kg out of 88.5 kg of CO2 was emitted from the clinker production phase. This shows that clinker production is the production phase that contributes the most to global warming. In the analysis of terrestrial ecotoxicity, result showed that numerous heavy metals that that are emitter into the air are great contributors to this impact category; few of these metals with high values are copper (61.5%), Mercury (11%), zinc (7.77%), nickel (7.53%), vanadium (7.06%). These metals are emitted at the raw material extraction, energy generation and transportation production phases. Fossil resource scarcity shows that the most used resources are coal, crude oil and natural gas and they are maximally used at the energy generation production stage.

In the endpoint assessment, characterization result showed the impact of 22 impact categories. These impacts were further classified into three damage categories based on area of significance to life (AoSL): human health, ecosystem and resources with values of 1.22E^{-6} DALY, 3.1E^{-9} species/yr. and 0.0231 USD2013 respectively. Disability-adjusted life years (DALY) represents the years of life spent or years of life damaged because of environmental impacts. Species/yr. denotes the species lost within a year in water bodies and the environment as a whole; USD2013 represent the currency used for the monetary value of economic loss leading to increase in prices as a result of continuous extraction of resources. Analysis of the damage to human health category showed that 67.3% of the damage to human health is as a result of emission of CO2 while the rest are from NOx, so2 ch4, particulates mater <2.5 μm and water; 70.1% of these emissions was from clinker production stage while the rest was for energy generation and transportation. The same trend was observed in the analysis of damage to ecosystem; 79.9% of the damage to ecosystem was found to be as a result of co2 emission while the rest are from NOx, SO2 CH4, methane and water; 77.8% of these emissions was from clinker production stage while the rest was for energy generation and transportation. This thereby establishes the fact that whatever will affect human health will equally affect ecosystem. As also seen in the midpoint emission, clinker production is the production phase has the highest contribution to impact consequently causing damage and CO_2 is the most significant pollutant. The analysis of resources shows that the resources that are maximally used are from the energy generation production phase and they are: crude oil (67.9%), natural gas (16%), hard coal (11.4%) and clay (4.19%). This shows that petroleum is the main fossil fuel used for the production of OPC.

The outcome reveals that emission from clinker production contributed immensely to global warming and consequently damage to human health and ecosystem. This study concludes that production processes with impact hotspots are clinker production and energy generation (fossil fuel and electricity) and the major pollutant is CO2 gas emission. The result of this study is in line with other similar studies (including those that do not implement the 2 approaches) carried out but there is variation in the result of the resources because of variation in the fossil fuel sources used for energy generation. Finally, it is recommended that using alternative fuels in place of fossil fuels can be a means to reduce the pressure on fossil resources. Incorporation of best available techniques (BAT) in cement production process, partial replacement of clinker constituent with pozzolans like fly ash are other strategies to reducing impact of cement production. Also, CO_2 gas emitted can be trapped, stored and used as input for industrial processes which will reduce global warming impact. Further study is the sensitivity analysis of environmental impacts of cement when alternative fuel and materials are used.

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Conflict of interest

Authors declare that there is no conflict of interest with respect to the study.

List of acronyms

LCA	Life cycle assessment
LCIA	Life cycle impact assessment
OPC	Ordinary Portland Cement
BAT	Best available techniques
ISO	International Standard Organization
LCI	Life Cycle Inventory
ReCiPe	an acronym for the developers: RIVM, Radboud University, CML and PRé Consultants
1,4 DCB	1,4-dichlorobenzene
AoSL	Area of significance to life.
DALY	Disability-adjusted life years

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Chapter 4

Fostering Education for Circular Economy through Life Cycle Thinking

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Abstract

Since 2002, the University of the Basque Country has supported several teaching experiences related to the so-called Life Cycle Thinking and Ecodesign in collaboration with local and regional public institutions and private companies. The implementation of a Master's Degree entitled 'Circular Economy: Business Application' constitutes a milestone in the framework of these teaching experiences. From the very moment the European Green Deal was approved and, subsequently, before the state and regional strategies were launched, thanks to our prior experience, we have been able to offer the postgraduate course required by our administration and companies. The courses have been specifically designed to provide education for Circular Economy for new graduates as well as professionals with backgrounds as varied as product manufacturing engineering, environmental engineering, business administration or economics. It aims to become a European reference in its goal of promoting Circular Economy, life cycle thinking, ecodesign, industrial symbiosis and sustainable development and, at the same time, support the transition to circular economy in our region. As a result, in just two years the master's degree has led to the creation within our university of a knowledge hub in Circular Economy, which hosts more than 20 research groups.

Keywords: Life cycle thinking, Circular Economy, life cycle assessment, lifelong learning, education for Circular Economy

1. Introduction

Circular Economy is a viable and promising alternative to the currently prevailing linear economic system. The fact of having a world with finite resources involves the need to adopt a sustainable economic system where sustainable processes must be prioritized [1]. Therefore, in this context of finite resources, Circular Economy seeks economic growth only if achieved in a sustainable way by keeping resources within closed cycles as long as possible. The significant importance of the decisions taken during the design phase of products and services results in the fact that over 80% of all product-related environmental impacts are originated in their design phase [2].

Meanwhile, the United Nations (UN) warns that if the world's population were to reach 9.5 billion in 2050, the natural resources of nearly three planets would be needed to sustain current and predicted lifestyle [3]. On the other hand, the Global

Footprint Network advises us that by 2020 the resources we had for the whole year were already spent by August 22th [4].

If that were not enough, we have been witnessing climate change for too many years. According to the Intergovernmental Panel on Climate Change [5], since the beginning of the industrial age, the average temperature of the planet has increased by 1°C. If the trend continues, it is expected to rise by between 3°C and 5°C by 2100. Furthermore, the extraction and processing of natural resources has accelerated significantly over the last two decades and, it is responsible for half of the impacts related to biodiversity loss, water stress and climate change [6]. Besides, our planet lives in a systemic crisis, with alarming social and economic inequalities, increasing rates of loss of natural biodiversity and cultural heritage, and a senseless growing pressure on natural resources and systems.

It is in this context that the concept of sustainability has gained in importance, with the steadily rising awareness of the necessity for a deep change that started in the end of the 80s. Parallel to this, the word "sustainability" seems to have become a multipurpose and valid term for any context, objective, argumentation or ideological-political stream [7].

Continuing the work started in 2000 with the Millennium Development Goals in 2015, the 2030 Agenda for Sustainable Development [8] was adopted by 193 countries at the United Nations (UN) General Assembly. The 2030 Agenda, our roadmap for the next 15 years, is acknowledged as transformative, universal and integrated, and it provides a shared blueprint for peace and prosperity for people and the planet, now and into the future [9].

The 17 goals of the 2030 Agenda for Sustainable Development cannot be achieved without systemic transformations on several fronts. Indeed, the 12th goal for sustainable development points at a responsible production and consumption system. Remaining within the paradigm of the linear system and establishing purely *ad hoc* changes will not be enough. In addition, the 4th goal for sustainable development, which reads "Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all", has always been kept in mind. This quality education and lifelong learning requires a continuous review-adaptation of our formative programmes.

Currently, the UN's Global Action Programme on Education for Sustainable Development [10] aims to contribute substantially to the 2030 development agenda, through two objectives:

- Reorienting education and learning so that all people have the opportunity to acquire the knowledge, skills, values and attitudes that empower them to contribute to a sustainable future.

- Strengthening education and learning in all agendas, programmes and activities that promote sustainable development.

In parallel with this UN Programme, the European Commission has launched the European Green Deal [11], a new growth strategy aiming to transform the European Union (EU) into a fair and prosperous society, with a modern, resource-efficient and competitive economy. Its main goals are, on the one hand, zero net emissions of greenhouse gases by 2050 and, on the other hand, keeping economic growth decoupled from resource use.

Besides, the new Circular Economy Action Plan [12] announces initiatives along the entire life cycle of products, such as targeting their design, promoting Circular Economy processes, fostering sustainable consumption and ensuring that all resources used are kept in the EU economy as long as possible.

The Spanish Strategy for Circular Economy 2030 [13], approved in June 2020, is fully aligned with the European strategy. In this way, all materials are used to the greatest possible extent, so waste generation is minimized. Thus, this Strategy contributes to Spain's efforts to achieve a sustainable, decarbonized, resource-efficient and competitive economy.

In terms of circular economy, the Basque Country is one of the leading regions in Spain. It underwent a traumatic industrial reconversion in the 1980s and since then has been committed to a development in harmony with the environment. It is worth highlighting the great compromise on the part of public institutions and companies in this task.

By means of the Agenda Euskadi - Basque Country 2030 [14], and the Strategy for Education for Sustainability of the Basque Country 2030 [15], the government of the autonomous region of the Basque Country is also aligned with the aforementioned 2030 Agenda.

In this context, in January 2020, the Basque Government issued the key points of its Circular Economy Strategy 2030 [16], and among these strategic objectives and challenges, it promoted research and degree studies at university level. More recently, the Basque Green Deal [17], issued in May 2021, proposes its own roadmap for a more sustainable future while addressing the post-pandemic crisis and leaving no one behind.

The mission of the Basque Country's Circular Economy Strategy, with a time horizon of 2030, is to promote the transition of the Basque Country towards a Circular Economy model and to position itself as a reference region in Europe. It aims to achieve positive results for our territory in three main areas:1) increasing the turnover of Basque companies regarding circular products up to 10,000 million Euros, 2) creating 3,000 jobs in the field of Circular Economy and, 3) reducing by 26% the carbon emissions associated with consumption.

The implementation of these strategies requires qualified people, either people who are working or people who are studying for a degree/master's degree. Qualified people and specialists in circular economy are required but also - and this is very important - that people working in other fields or studying other disciplines are aware of this new paradigm of Circular Economy. Circular Economy requires a systemic change and that change will only be achieved if the majority of people are aware of this need and have enough knowledge on the kind of actions to be taken.

Since Education for Sustainable Development constitutes a mature field of study, scholars aiming to teach sustainable development can draw on many degrees in Education for Sustainable Development. On the contrary, despite the overall Circular Economy literature, research on Education for Circular Economy is still somewhat limited. Currently, with at least 850 articles published in academic journals regarding Circular Economy, academia is making efforts to include that subject in diverse teaching programs [18].

Therefore, the development of a master's degree in Circular Economy focused on Product Lifecycle Thinking is the answer to the environmental, social and economic needs of our industry and society. A secondary objective of the master's degree is to form a group of professors from different disciplines to integrate the principles of Circular Economy education in all bachelor and master degrees at the university.

The innovative aspect of the experience is that it is a long-standing, successful and scalable experience. It is also transferable to other universities or higher education institutions.

This article presents first a definition of the concepts of Circular Economy and the Product Lifecycle Thinking, together with a perspective on the relationship between Product Lifecycle management (PLM) and Circular Economy. Second, presents a contextualization of the various studies and innovation projects related to Ecodesign and Circular Economy carried out at the Faculty of Engineering of Bilbao. Third, presentations of other relevant European studies that offer programs with partial or general similarity are listed. Finally, the last part gives a brief overview of the Master in "Circular Economy: Business Application" of the University of the Basque Country, including the intended learning outcomes together with a summary of the course related to… with a detailed description of each course.

2. What gives circularity to the product life cycle thinking?

The idea of Circular Economy is an integral vision that helps us to rethink our economy and our society. Therefore, it is not a question of "circularizing" the economy but of "circularizing" society [19].

Therefore, Circular Economy constitutes a driving incentive to this transformation and contributes to achieve the Sustainable Development Goals (SDGs) of UN 2030 Agenda. It offers a holistic framework to redesign the system, a new model that would take us into the "humanity's sweet spot" within Kate Raworth's "doughnut" [20] of social impacts and needs (**Figure 1**).

In principle, Circular Economy redefines the relationship between economy, society and nature. Its model distinguishes economic growth from natural resource depletion and ecological overload. Circular Economy aims to eliminate accumulated imbalances in the linear system and it combines economic prosperity with environmental caution. The concept of Circular Economy is based on the fundamental and obvious assumption that resources are limited and they must be preserved for future generations. It mimics nature by cycling resources. This requires sustainable consumption and production based on the so-called eco-design or environmentally responsible design [1, 21].

According to the Ellen MacArthur Foundation, "Economics by design must be restorative and aim to maintain products, components and materials at maximum utility and value, differentiating technical from biological cycles" (**Figure 2**).

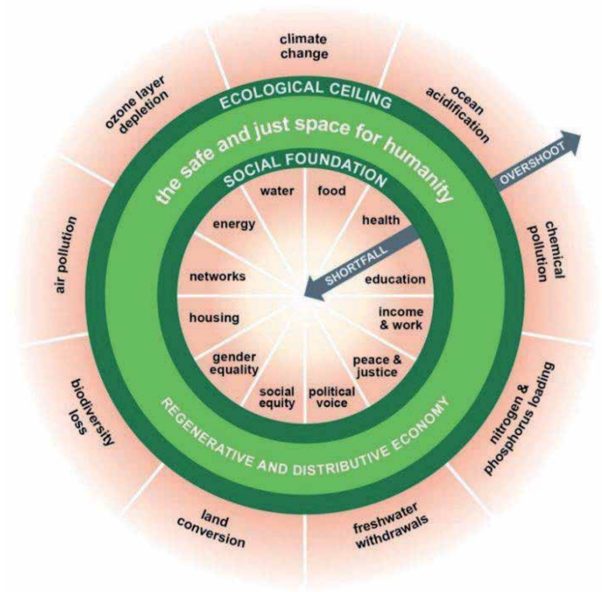
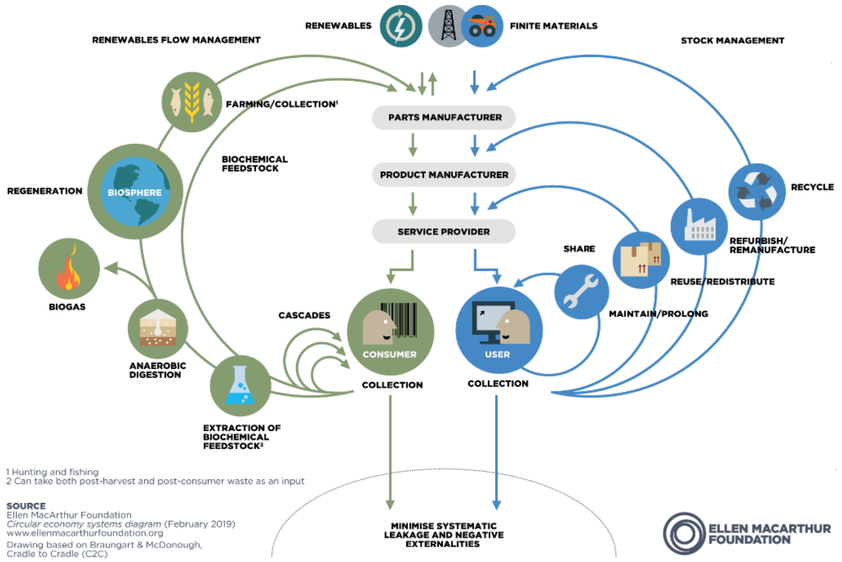


Figure 1.
The doughnut of social impacts and needs. Source: Kate Raworth, doughnut economics [20].



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input

SOURCE
Ellen MacArthur Foundation
Circular economy systems diagram (February 2019)
www.ellenmacarthurfoundation.org
Drawing based on Braungart & McDonough,
Cradle to Cradle (C2C)

Figure 2.
Diagram of circular economy systems. Source: Towards the circular economy. Economic and business rationale for an accelerated transition [1].

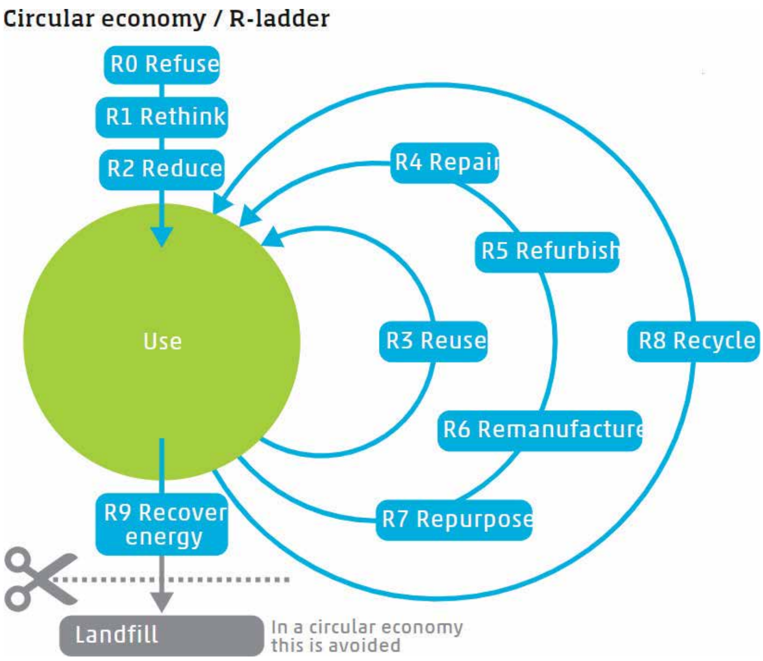


Figure 3.
R-ladder of circularity strategies. Source: Netherlands environmental assessment agency [22].

In the last decade, many companies in different sectors in Europe have opted for circular models through five fundamental axes [22]: circular entries, extension of product use, recovery of resources, platforms for sharing and product as a service.

In other words, companies are moving from the linear model of extracting, making and throwing away, to the circular model highlighted by the 9R Framework of Circular Approaches or the so-called 10R ladder of circularity strategies [6, 23].

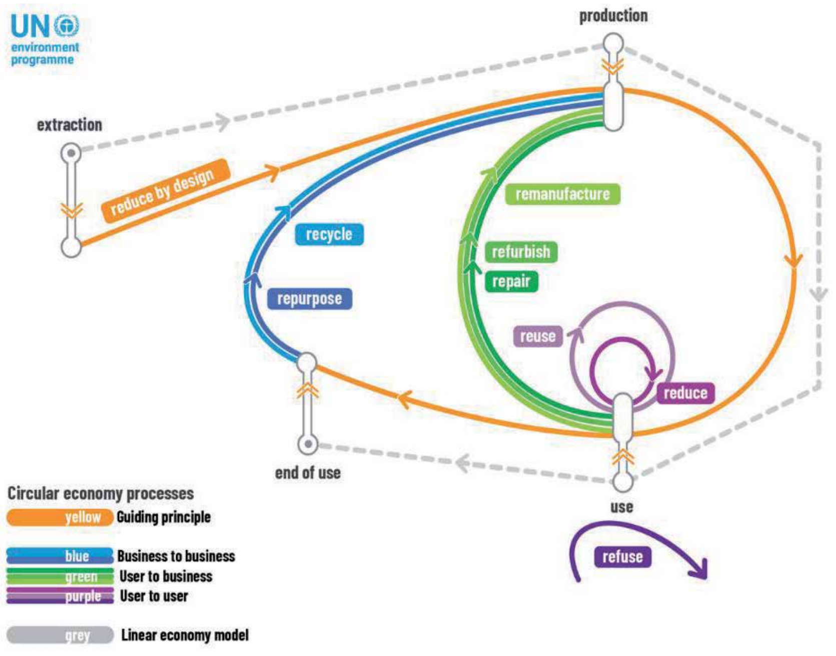


Figure 4.
Circularity diagrams. Source: United Nations environmental Programme's circularity platform [6].

From greater to lesser impact, these strategies are: R0 refuse, R1 rethink, R2 reduce, R3 reuse, R4 repair, R5 refurbish, R6 remanufacture, R7 repurpose, R8 recycle, R9 energy recovery (**Figures 3** and **4**).

In the circular model, apart from recycling, with the emphasis lying on reduction and reuse, it is necessary to make greater efforts. The concept of circular economy covers the entire lifecycle of the product, so it requires a much broader and systemic approach, with a special emphasis on education, than the traditional approach to production. For instance, regarding the fashion industry, a key question would be: Should our model of sustainability clothing be based only on the recycling container?

3. Product life cycle and circular economy

For manufacturers, product design has traditionally meant "design for manufacture". In other words, producers want to place on the market quality products as quickly as possible and at the lowest possible cost, without worrying about what will happen at the end of the product's life. Instead, "design for circularity" considers the entire life of the product, from design to production, through its use and its reuse, to the end of life. Circularity is a feasible way to serve both, people and the planet, while still making a profit, and has become a "hot topic" in engineering studios as well as boardrooms and legislative chambers [24, 25].

A challenge that needs to be addressed in Product Life Cycle Management (PLM), in a decentralized knowledge intensive environment, is the collaboration between the stakeholders involved in all product lifecycle activities and in an extended enterprise context, this collaboration involves, among others, the network of researchers, designers, producers, retailers and consumers. Technologies such as the Internet of Things (IoT) or Big Data could enable this challenge. At the same time, new challenges related to growing concerns with sustainability issues and the increasing significance of Circular Economy approaches, which require improved products that can be used longer and with multiple lifecycles are emerging [26]. This scenario poses challenges to future PLM systems, especially those intended for small and medium-sized enterprises (SMEs), which have limited internal resources and strongly rely on collaboration with external partners, suppliers and customers.

Therefore, PLM has become an important Circular Economy driver [27]. It has a paramount importance because PLM involves the whole lifecycle of a product, consumer good or service, from cradle to cradle and it is the only management system capable of addressing all the sustainability information necessary to pass from a linear design and manufacturing concept to a circular one.

PLM systems are information management systems that can integrate data, processes and business systems in extended enterprises. PLM systems have become interesting supporting tools in the transition to the Circular Economy, as they help integrating information across multiple life cycles as well as various stakeholders in the value chain [28].

In summary, when in the late 1970s Walter R. Stahel coined the term “cradle to cradle” C2C [29] and in 2002 Michael Braungart and William McDonough published a book entitled “Cradle to Cradle: Remaking the Way We Make Things” [30], a manifesto for cradle-to-cradle design that exposed specific details of how to achieve the model, few would have imagined the importance of the PLM through the entire Lifecycle and even less the introduction of sustainability concepts involved in the Circular Economy definition, such as reducing, reusing, repairing, remanufacturing, repurposing, recycling, etcetera [31].

4. From education for sustainable development to education for circular economy

Both, younger professionals, who have just started working, and senior professionals need to integrate circular economy in their daily activity. However, they have little or no knowledge on this field because the concept of circular economy did not exist at the time they completed their studies. Therefore, special efforts must be made in order to create a knowledge and competence base to foster circular innovation at all levels of education as well as to promote lifelong learning in this field. The integration of Circular Economy and Systems Thinking into the curricula of higher education institutions should be encouraged to help to raise sustainability awareness and transform our mentality [18, 32].

According to the Ellen MacArthur Foundation, the way people think shapes the world around them and, people’s ways of thinking are built throughout their process of learning. The transition from linear to circular economy requires people to transform the way they create products, services, and systems.

In order to support people’s learning about Circular Economy, the Ellen MacArthur Foundation places an emphasis on interdisciplinary, project-based, and participatory approaches [33]. This Foundation’s aim is to help people understand how they can influence the complex systems around them.

According to other experts such as Sitra, the Finnish Innovation Fund for a sustainable future, to create a Circular Economy society, circular industries need a new kind of expertise, with co-operation between silos, a development of the operating environment and a general change in attitudes and operating methods. Professionals, experts and decision-makers, both now and in the future, will play a decisive role in building a new future, and education plays an important role in preparing those experts on Circular Economy for our near future [34].

5. Master's degrees related to circular economy in Europe

Several Master's degrees in prestigious international universities in Europe have served as inspiration and reference for preparing and offering the Master's degree in Circular Economy at the University of the Basque Country. Postgraduate degrees on Circular Economy exist all over the world, mainly in North America, Oceania and Asia, but as nearby courses are our immediate competitors, only the European Master's degrees have been listed.

Before presenting these degrees, it should be highlighted again that Education for Circular Economy is still in its infancy. It is foreseeable that in the short-medium term the offer of postgraduate degrees will increase. Regarding the number of credits assigned to them or regarding their theoretical and practical content or interdisciplinarity, there will be substantial differences among these degrees. In addition, these degrees will offer a variety of approaches to the subject, this is, with general contents or specifically focused on economics, engineering or marketing.

The European studies that have inspired and served as main reference for our master's degree proposal constitute the CIRCLE program, which is an Erasmus Mundus International Master's Program on Circular Economy. The objective of the Master's Programme on Circular Economy is to offer international and interdisciplinary studies at the highest level, which will allow participants to make an essential contribution to understanding and proposing solutions to problems in order to support the transition towards a sustainable society.

The following is a summary of the main study programs offered in Europe related to Circular Economy:

ERASMUS MUNDUS CIRCLE PROGRAMME

- Website: https://www.jointdegree.eu/en/circle-erasmus-mundus-international-masters-programme-on-circular-economy/
- Degree awarded: Master of Science in Technology
- Credits: 120 ECTS
- Duration: 2 years
- Partner universities:
  - University of Graz (coordinator) (Austria)
  - Chalmers University of Technology (Sweden)
  - Delft University of Technology (The Netherlands)
  - Leiden University (The Netherlands)
  - Norwegian University of Science and Technology (Norway)
  - Curtin University (Australia)
  - Tsinghua University (China)
  - Waseda University (Japan)

FINLAND
Master's Programme in Circular Economy

- Website: https://www.lut.fi/web/en/admissions/masters-studies/msc-in-technology/environmental-technology/circular-economy
- Degree awarded: Master of Science in Technology
- Credits: 120 ECTS
- Duration: 2 years
- Campus: LUT University (Lappeenranta-Lahti University of Technology)

UNITED KINGDOM
Technology Innovation and Management for a Circular Economy MSc

- Website: https://www.cranfield.ac.uk/courses/taught/technology-innovation-and-management-for-a-circular-economy
- Degree awarded: Master of Science in Technology, Postgraduate Diploma and Postgraduate Certificate
- Duration: 2 years
- Campus: Cranfield University

UNITED KINGDOM
Innovation, Enterprise and Circular Economy MBA

- Website: https://www.brad.ac.uk/courses/pg/innovation-enterprise-and-circular-economy/
- Degree awarded: Master of Business Administration
- Duration: 2 years
- Campus: University of Bradford - Faculty of Management, Law and Social Science

THE NETHERLANDS
Circular Economy: An Introduction + Engineering Design for a Circular Economy

- Website: https://www.edx.org/course/engineering-design-for-a-circular-economy
- Duration: 7 + 6 weeks (free course)
- Campus: Delft University of Technology TUDelft

SPAIN
Master's Degree in Circular Economy

- Website: https://www.ubu.es/master-universitario-en-economia-circular-semipresencial
- Degree awarded: Master of Science in Economics
- Credits: 60 ECTS
- Duration: 1 years
- Campus: University of Burgos (Faculty of Economics and Management)

ITALY
Master Circular Design

- Website: http://www.mastercirculardesign.it/
- Degree awarded: Master of Science in Technology
- Credits: 60 ECTS
- Duration: 1 years
- Campus: Iuav University of Venice

THE ELLEN MACARTHUR FOUNDATION - Network Universities

The Ellen MacArthur Foundation is committed to working with universities and higher education institutions worldwide to enable the transition from a linear to a Circular Economy. Together, through collaborative work, they develop, share, and scale Circular Economy learning.

Website: https://www.ellenmacarthurfoundation.org/our-work/activities/universities.

EIT RAW MATERIALS

EIT RawMaterials Academy goes from innovative education projects launched via calls and run by the Innovation Community's partners to a number of centrally operated projects across some European universities. Circular Economy plays a predominant role in the degree programs offered.

Website: https://eitrawmaterials.eu/eit-rm-academy/labelled-masters/

6. The master's degree in circular economy at the University of the Basque Country

6.1 Starting point of the master's degree in circular economy

The University of the Basque Country is a public research university, deeply rooted in Basque society, open to the world, with an intellectual leadership and an ethical and social commitment. Its mission is to nurture a cultivated population by providing quality education and training based on knowledge, innovation and equity.

As it happens with other organizations, the University of the Basque Country considers UN 2030 Agenda and its SDGs as a model or framework that can accommodate the high quantity of the programmes implemented in recent years. In this area, certain degrees and research projects showed that SDGs were not unrelated to who we were or what we did when the UN initiated this agenda in 2015. These degrees and projects promoted a human rights culture, gender equality policies, the development of university cooperation, as well as environmental management or joint projects alongside organizations operating in the third sector [6].

Aligned with the policies mentioned in previous sections, the University of the Basque Country has supported different teaching experiences related to the so-called Life Cycle Thinking or Ecodesign in collaboration with some local Institutions in the last two decades.

The kick-off for these experiences was established in 2002 with the foundation of the Ecodesign Learning Center at the Faculty of Engineering in Bilbao [35].

The Basque Ecodesign Center (www.basqueecodesigncenter.net) is a partnership framework between firms in the private sector and the Basque Government. It aims to foster the design and execution of innovative ecodesign projects. Besides, Ihobe (www.ihobe.eus/home) a publicly owned company under the auspices of the Basque Government's Ministry for the Economic Development, Sustainability and Environment supports the Basque Government in the implementation of its environmental policy and in the spreading of the environmental sustainability culture in this region.

Boosted by Ihobe, the Basque Ecodesign Center and the Sustainability Directorate of the University of the Basque Country, in October 2019 the university launched the first edition of a postgraduate course about circular economy (consisting of 36 ECTS. At that moment, a new master's degree with 60 ECTS for the next academic year was on its way. This new master, entitled "Circular Economy: Business Application", places a special emphasis on the aspects related to ecodesign and product life cycle thinking [36].

It should be noted that these studies were a necessity for the Basque Country, as there was no master's degree or training of these characteristics neither in our region nor in neighboring regions, and our industrial fabric needed this type of officially regulated courses.

6.2 Facts of the master's degree in circular economy; business application

The master's degree in Circular Economy [36] takes place from September to June (**Table 1**) plus the Master's thesis to complete the 60 ECTS required to obtain the degree.

The maximum number of students has been fixed to 25 and more than 35 associate professors, full professors and professionals from the governments and industrial sector take part in it. Candidate students are sought among engineers and economists working in local-regional industry, service companies or public administration. Courses are imparted at the Faculty of Engineering and the Faculty of Economics and Business in Bilbao.

The courses are programmed with participatory and active learning methods such as flipped classroom, jigsaw techniques or Problem Based Learning (PBL). Other aspects such as interactivity, non-dogmatism and reciprocity are taken for granted.

Regarding the organization of teaching, each subject has a digital learning platform or course management system (Moodle) where teachers can upload the content of their classes as well as additional material for students to consult previously (flipped classroom method) or later. In addition, classes can be followed online through the university's own videoconferencing platform integrated in the course management system. In this way, students who are confined or unable to attend classes for justified work reasons can follow the explanations of the teachers from home.

	Course	ECTS credits
1	Circular Economy: General Context. Eco-innovation as a Business Opportunity.	6
2	Environmental Impacts Derived from the Production-consumption of Products and Services	3
3	Environmental Management Tools in the Company	3
4	Ecodesign and Circular Economy	3
5	Life Cycle Thinking 1: Tools for Calculation and Communication	3
6	Life Cycle Thinking 2: Quantification of the Product Environmental Footprint	3
7	Circular Economy and Industry 4.0	3
8	Circular Economy in the Company: From Ecodesign to Product Commercialization	6
9	Circular Economy in the Company: Sustainable Entrepreneurship, Business Models in Circular Economy	3
10	Circular Economy Initiatives. Business Cases	9
11	Practical Workshops on Circular Economy	6
12	Master's Thesis	12

Table 1.
Courses of the master's degree in circular economy for the 2020-2021 academic year.

As a whole, the course is evaluated by means of a survey prior to the commencement of the course, together with a special face-to-face session at the end of the course in which the students present their learning experience and from which the strengths and weaknesses of these master's degree are extracted. In addition, at the end of each course a small survey is carried out to find out the students' opinion of the teaching methodology.

Besides, the academic board of the master's degree offers voluntary internships in companies. Only a small number of students are interested in these internships because the majority of them are professionals with more than 10 years of experience.

The academic board of the master's degree is considering the possibility of the course becoming an Erasmus Mundus master's degree in the future. This would require teaching agreements with several European universities. It is not considered urgent because the initial intention of the sponsors is to respond to a local educational need and not so much the exchange and mobility of students and professors.

In summary, the main strength of the course is the multidisciplinarity of its topics and courses, together with the wide representation of professionals representing the most important industrial sectors of the region.

6.3 Life cycle thinking: ecodesign and life cycle assessment

The transformation towards a more circular business model requires information about the inputs and outputs of different systems and processes, all of this together with the measurement of their impacts, data management and data exchange across the value chain.

What is the right way to assess and communicate impacts? Through the concept, acknowledgement and implementation of Life Cycle Thinking incorporates this evaluation of the environmental, economic and social aspects of the products (material goods or services).

Life Cycle Thinking allows industries to go beyond traditional linear thinking and focuses on production and disposal by including environmental, social, and economic impacts of a product over its entire life cycle, that is, from cradle to grave and, consequently allowing a more holistic assessment, highlighting, comprehension and possible prevention/reduction of impacts [37].

The courses closely related to Life Cycle Thinking make up 9 ECTS, which are divided into 3 modules consisting of 3 ECTS:

Ecodesign and Circular Economy

1. Introduction to the concept of ecodesign: basic principles and implications for the design of material products and services.

2. Standards in ecodesign.

3. Ecodesign methodology.

4. Ecodesign and companies: Integration of the Ecodesign in the enterprise management systems. Product-service systems.

Life Cycle Thinking 1: Tools for Calculation and Communication

1. Product life cycle: background and concepts. Life cycle and extended producer responsibility. Implications for the product designer.

2. Methodological principles of Life Cycle Analysis based on international standards. Life Cycle Assessment Software: Open LCA and SimaPro.

3. Communication and marketing with a Life Cycle approach.

Life Cycle Thinking 2: Quantification of the Product Environmental Foot-print

1. Social and environmental impacts.

2. Calculation of the environmental footprint of products and organizations. Combination of Life Cycle Assessment tools and Input–Output sector tables. Global Multi Regional Input–Output methodology (GMRIO).

3. Sustainable Product Design Tools. Product design cycle for a Circular Economy.

4. The R framework in Circular Economy. Reuse, Repair or Recycle + Restructure, Revalue, Relocate and Reconceptualize.

Overall, emphasis is made on how ecodesign serves to reduce the environmental impacts associated with a product along its whole life cycle. It also points out the relevance of servitization - or Product System Service (PSS) - as a more sustainable new business model. Within an ecodesign framework, it also describes the methodology for LCA thoroughly using different software tools. It also provides a deeper understanding of these matters by the calculation of different footprints. All of this will enable students to get a wide and deep overview on the concept of Environmentally Conscious Design.

6.4 Intended learning outcomes or specific competencies

When drawing up the Master's program, the aim was to ensure that students become experts in the challenges that the new Circular Economy poses for local-regional companies. Consequently, the most relevant specific competencies (knowledge, skills, and attitudes) that students must have acquired at the end of their Master's studies are the following:

- To define the concepts of Circular Economy, Sustainable Economy, Low Carbon Economy, Industrial Symbiosis and Eco-Innovation.
- To understand and explain the changes involved in the transition from a linear to a circular type of economy, as well as to recognize the opportunity they represent.
- To identify the current applicable environmental regulations (air, water, waste and soil) in order to carry out proper environmental management in the company.
- To define the concept of ecodesign and to become aware of the environmental, economic and social implications of product design.
- To apply the ecodesign methodology and manage the tools available for ecodesign in the industrial field
- To define the concept of life cycle and identify the phases of the life cycle of a product, as well as list the regulations of the Life Cycle Analysis.
- To know and apply the evaluation methodologies and software tools for product life cycle analysis.
- To formulate guidelines for communication and marketing with a life cycle approach.
- To define and understand corporate and competitive strategies to integrate the environmental variable in the company and select the most appropriate strategy for each particular case.
- To identify business opportunities in the field of the Circular Economy for different sectors, stakeholders and design proposals.

These intended learning outcomes are fully aligned with the targets proposed by some European universities that are considered to be at the leading edge in this area of knowledge and education [38–40]. The master's degree covers the proposed seven Circular Economy competencies for design to a greater or lesser extent. These competences are the following: Circular Impact Assessment, Design for Recovery, Design for Multiple Use Cycles, Circular Business Models, Circular User Engagement, Circular Economy Collaboration, and Circular Economy Communication.

7. Other achievements derived from the master's degree in circular economy

We are pleased to see that the master's degree in Circular Economy has promoted other important projects related to Education for the Circular Economy and SDGs.

The postgraduate course has been the catalyst for various initiatives that are complementing the university's educational initiatives in other areas of interest such as research and knowledge transfer.

These achievements can be summarized as follows:

- The postgraduate course is the nexus of the so-called Circular Economy Knowledge Hub at the University of the Basque Country.

- As a complementary activity to the master's degree, the summer course "Circular Economy and its opportunities for the public sector in the post-pandemic scenario" will be organized in June at the University of the Basque Country.

- A new university-company research laboratory has started its research work based on Circular Economy and Green Energy, the involved researchers and students came mainly from the master's degree course.

- The postgraduate course also connects the academia with private small, medium and large enterprises, thanks to the internships carried out by the Master's students in them.

- The master's degree is working as a catalyst for the work of several research groups on topics related to Life Cycle Thinking (https://www.ehu.eus/en/web/lifecyclethinking/), Secondary and Raw Materials, Sustainable Economy, etc.

- In addition, the professors of the master's degree course give educational support to the Basque Circular Hub (http://www.basquecircularhub.eus).

In addition, the social and economic impact of the course is clear. Every year, 25 students are trained to become experts in circular economy and will become the drivers of the circular change in their respective companies.

8. Conclusions

From previous sections it can be concluded that postgraduate studies in Circular Economy were a necessity and continue to be an ongoing reality at the University of the Basque Country.

These studies are ambitious and they are highly developed in the fields of Ecodesign and Life Cycle Thinking. This, it is expected that graduated students will help in advancing towards a sustainable society as they are incorporated into public services, higher education institutions, research centers or industry. This will enable not only a more efficient integration of the Circular Economy and Life Cycle Thinking concepts into our community, but it will also allow enterprises to get ahead of the many legislative changes that are expected to occur in the near future.

The master's degree has fostered numerous initiatives promoting knowledge transfer in Circular Economy.

This is a pioneering experience in Southwestern Europe, and in the near future, alliances will be sought with other European universities to offer a joint degree or at least to be able to offer mobility to students so that they can experience other academic realities.

The currently ongoing global pandemic of COVID-19 further encourages us to rethink our current economic system and provide a resilient approach to battle the deep economic recession that our society is facing. The NextGenerationEU recovery plan can help but it will take the whole of society working together. In this context, the postgraduate studies in Circular Economy offered by the University of the Basque Country may serve as a common ground to boost a coalition between academia, industry and public institutions and exploit the full potential of a circular model.

Because of the work carried out, in just two years the master's degree has led to the creation within our university of a knowledge hub in Circular Economy, which hosts more than 20 research groups.

In the near future, and continuing with the product life cycle approach, we hope to promote more initiatives that provide us with opportunities for the challenging sustainable transformation of our society.

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Chapter 5

An Innovative Visualization Tool to Boost and Monitor Circular Economy: An Overview of Its Applications at Different Industrial Sectors

Augusto Bianchini and Jessica Rossi

Abstract

The quantification of the circular economy and sustainability is a relevant aspect at different levels of applications: (i) the companies need to evaluate and improve the environmental, economic, and social impacts of their products and processes; (ii) the financial bodies must have quantitative information about the potential and risks of different proposed initiatives to select the optimal opportunity; and (iii) the policy-makers must be guided for the coherent definition of strategies at regional, national and international scales, setting realistic targets and measuring their effectiveness. However, the lack of comprehensive and robust approaches to quantify circular economy makes it challenging to apply quantitative methods and indicators in different contexts and compare the results, with the risk of limiting the practical implementation of circular initiatives due to unknown and/or unclear potential and contribution. The ViVACE® tool (Visualization of Value to Assess Circular Economy), developed by the authors, is a promising and effective means to collect data in a systematized manner, helpful to assess sectorial and cross-sectorial indicators about sustainability. It has been applied to different industrial sectors (e.g., plastics, food processing, textile) for different purposes. These applications are described in detail to highlight the potential, versatility, and implications of the proposed tool in boosting the effective transition to a circular economy.

Keywords: circular economy, sustainability, indicators, performance measures

1. Introduction

Several definitions of circular economy (CE) exist in the literature, mainly focusing on different aspects of its core concept, firstly defined in the 1970s and then developed over time among different schools of thought [1–3]. The European Commission has delineated a simple but complete definition of CE in 2015, which specifies that [4]:

> *"In a circular economy, the value of products and materials is maintained for as long as possible. Waste and resource use are minimized, and when a product reaches the end of its life, it is used again to create further value."*

In the last two decades, CE has gained great attention and commitment from international governments, policy makers, and institutions. They identified in this economic model a great opportunity to: (i) build long-term resilience and sustainability, (ii) determine business and economic competitiveness, and (iii) provide societal and environmental benefits [5, 6]. In 2020, the European Commission launched "A new Circular Economy Action Plan for a cleaner and more competitive Europe" [7], which states that going mainstream the CE will significantly contribute to the achievement of a climate-neutral society and economy, according to the European Green Deal objective [8]. In [9], the benefits and contribution of CE on the pillars of sustainability have been deeply analyzed, highlighting how CE directly or indirectly addresses the achievement of a relevant number of the 17 Sustainable Development Goals (SDGs) targets, described in the United Nation Agenda 2030 to attain sustainable development in a balanced manner considering the interrelated and holistic nature of the environmental, social and economic dimensions of sustainability.

Since each business model is, by definition, focused on creating and capture value, generating sustainable and competitive advantages through product and process innovation, the enterprises have a fundamental and active role in the transition to a CE, which guides the innovation to transform the way products are designed, manufactured and used along their entire life-cycle [10, 11]. To enable an effective and successful circular strategy in the industrial sector, all actors in the supply chain should take part in the transition [12]. In [13], a literature review on the practical application of CE in the manufacturing industry is provided: even if empirical case studies, focusing on applications for narrowing and closing the resource loops, increase over time, it has been highlighted that the implementation of CE in the manufacturing sector is still sporadic and it is not possible to find in literature any kind of systematized recommendations able to guide companies in the successful CE transition of their business models. To overcome the lacking of comprehensive analyses to identify the most impactful CE actions on a specific business model building block, the reference [14] provides a list of nine general managerial insights to support companies in shifting to the practical implementation of CE in their business models.

Several studies are focused on the identification of the main barriers to the design and implementation of successful CE strategies [15–17]. One of the most recognized limits for the overcoming of the CE practice-theory gap is the lack of clear and consistent methods to actually assess the circularity and sustainability of products, processes, business models, and strategies. The quantification of the achieved circularity level involves different scales, from the micro/meso scale (companies, supply chains, industrial parks, etc.) to the macro scale (cities, regions, countries, etc.). At a company level, quantitative information is fundamental to rapidly and effectively make decisions about innovations and investments [18]. The importance of assessing initiatives and practices is greater in the CE context, which is by nature characterized by a network of interconnected companies; consequently, a holistic and transparent method to measure the impact of CE becomes fundamental [19]. At macro-level, the primary need for policy- and decision-makers is a coherent definition of strategical visions at regional, national and international levels, setting realistic targets and measuring their effectiveness [20, 21].

Several approaches and indicators to measure circularity have emerged in the last years. Numerous recent studies reviewed the existing literature about circular indicators and metrics, dividing them according to the system level (micro, meso, macro) and, within each level, according to the sustainability pillars that they assess (environmental, economic, and social) [19, 22–24]. These papers highlight that hundreds of indicators to assess CE exist, but there are still two main issues for their widespread implementation, ensuring a suitable CE assessment. (i) The first issue comes to the assessment of CE within the same scale/level. In particular, high diversity and fragmentation of approaches and metrics have been identified, making it difficult to compare the industrial applications in which such indicators and methods are used [19, 23]. The causes of this fragmentation are mainly two. The first element is related to the big concept of the CE umbrella: hundreds of CE definitions exist, and its paradigm is developing without an overall consensus regarding circular actions and aspects [25]. This diversity in the theoretical background is reflected in the industrial adoption of CE, which provides very specific case studies. Consequently, these peculiarities also require a tailored assessment framework, challenging to be replicated in other contexts. The second element that determines fragmentation in CE assessment at the same scale is linked to the lack of standards. In fact, only practical but not official guidance on CE principles, practices, and monitoring have been published. Only the British Standards Institution launched a new standard about CE, the "BS 8001:2017 – Framework for implementing the principles of the circular economy in organizations—Guide" [26], but international standardized guidelines, and their transposition at a national level, are still under development and are not expected before 2022. (ii) The second issue recognized in literature in the use of circular indicators consists of the connection among system levels, allowing the identification of the links between the micro- and macro- level metrics [22].

Often, in the literature reviews about available circular indicators [19, 22, 27], a significant statement about the difficulties and complexity to use and implement these metrics is highlighted and refers to the relevant need to collect and process a large quantity of data (typically related to aspects not yet monitored in the industry), characterized by suitable robustness and consistency. To overcome this barrier, the authors developed an innovative visualization tool ViVACE® (Visualization of Value to Assess Circular Economy), published in 2019 [28] and registered as a mark in 2020, able to intuitively provide quantitative information about CE to guide the decision-making process and monitor the impacts at the described scales. Starting from the question of why such a recognized and consolidated concept was so difficult to put in practice, an analysis of the existing visualization tools to explain the CE paradigm was conducted (considering both grey and scientific literature) to select the most suitable to boost an effective and successful transition to a more sustainable production and consumption model. This analysis highlighted the lack of three main features, without which the demonstration of the benefits and limits to shift to a CE should be challenging, above all for practitioners. These missing characteristics in the available tools are: (i) the capacity to provide quantitative information about circularity; (ii) the possibility to be adapted to different industrial sectors; and (iii) having correspondence to what effectively occurs in real industrial contexts. From this framework, the development of a new visualization tool started.

After a little more than a year from the building of the tool, the authors applied it to different industrial sectors, confirming its features and capacity to boost the practical implementation of CE and to feed suitable and significant indicators to assess practice performance. The chapter aims to present an overview of the application fields of the ViVACE® tool, highlighting its main advantages, possible improvements, and the main implications to reach the purposes of different levels in the CE field. After this first introduction, which aims to introduce the most challenging aspects in quantifying to a CE, limiting its practical transition, the remaining parts of the chapter are structured in the other three sections. Section 2 presents the methodological approach adopted by the authors to boost an effective shift to a CE through the adoption of the innovative tool ViVACE® able to provide useful quantitative information. In particular, this Section describes the main implemented/ongoing applications of the tool in different industrial sectors, according to several purposes. Section 3 analyses and categorizes the previously described applications to demonstrate the potential of the tool in terms of coverage of, e.g., different sectors, actions within the CE umbrella concept, and scales. This standardization supports an easy replication of the tool in other contexts and upscaling according to different implications. Finally, Section 4 describes the main conclusions, recapping the contribution that the wide use of the proposed tool could provide for the identification and measurement of unexplored circular initiatives through a quantitative demonstration of their effectiveness.

2. Application of ViVACE® to different industrial sectors and circular initiatives

The general elements that compose ViVACE® and the methods used to build it are deeply described in [28]. **Figure 1** shows a generic "stage" of the tool, representing the material flows in a company or a part of a specific industrial process (the graphical

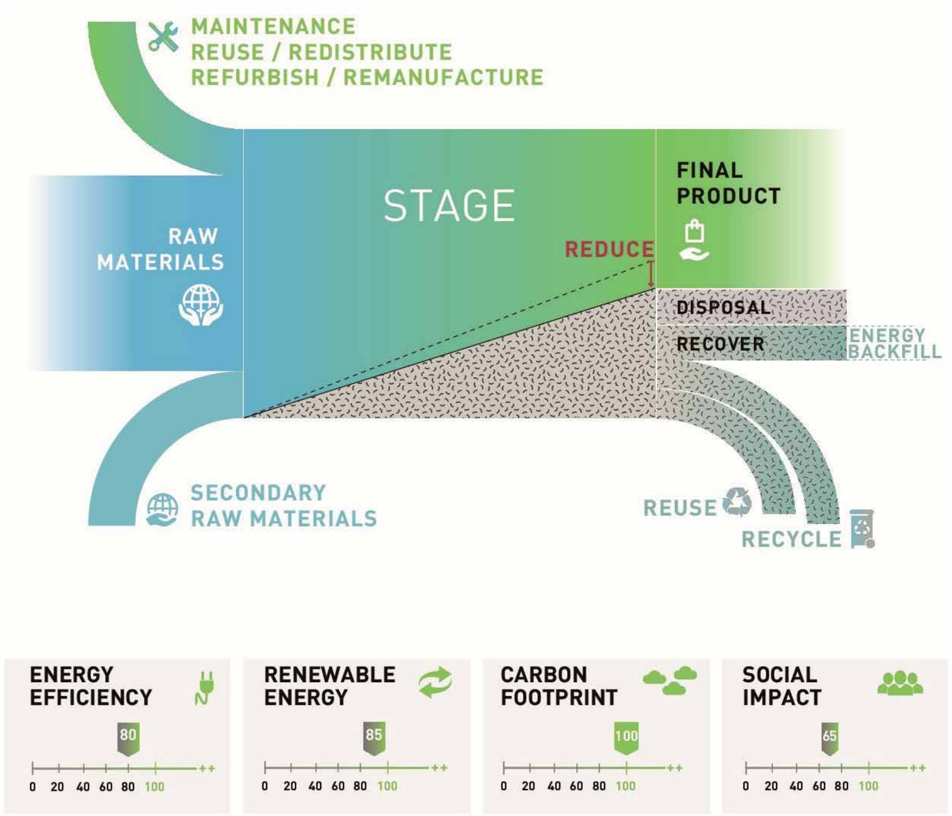

Figure 1.
Representation of a generic stage according to ViVACE® tool [28].

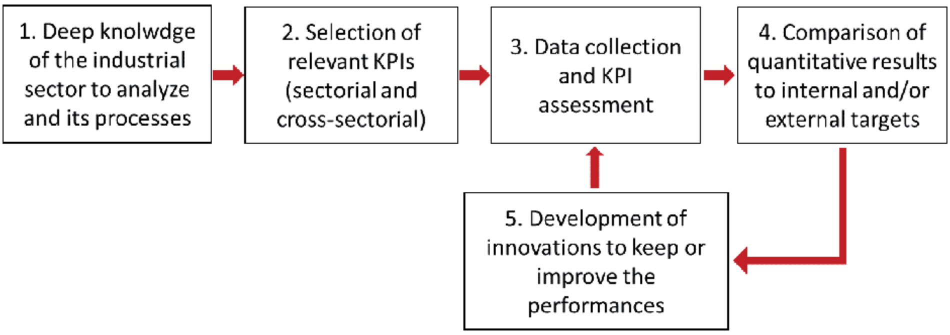

Figure 2.
Methodological steps, based on ViVACE® tool, to support the transition to a CE.

width is proportional to the actual flow) and completed with the measurement of some transversal KPIs.

The tool was already used to analyze circular case studies available in the literature, with the aim to show its potential and versatility [29]. The lack of accessible and quantitative information limits the application of the ViVACE® tool, which has been only qualitatively set. However, without a quantitative analysis of those case studies, for example, with the use of relevant KPIs, it is not possible to compare the improvements generated by the "linear" scenario or by different circular opportunities.

On the contrary, the authors' approach is based on the quantification ensured by the use of ViVACE® tool. In particular, the typical methodology used to address and support an effective transition to a CE is based on the steps shown in **Figure 2**. These methodological steps have already been implemented in different industrial contexts, providing interesting results.

This Section describes the application fields in which the ViVACE® tool has been implemented. For each application, which varies a lot for sector and type of action, the context is described, highlighting the barriers and some limiting aspects for the development of circular actions. Moreover, the implementation of ViVACE® tool and its main results are reported to understand its contribution in accelerating the transition to a CE in the considered sectors.

2.1 Phosphorus management

Phosphorus (P) is a main raw material for fertilizer production: with its irreplaceable properties, it ensures proper plant growth, providing food directly for human consumption or for animal growth, becoming human food in a second term. It derives that P represents a crucial building block for food security. Due to its importance, but also its crucial issues, P is listed as a critical raw material for the EU economy [30]. The criticality is given by two main priority aspects to be considered for P management in Europe: P is a non-renewable resource since a time misbalance exists between P geological cycle (million years) and the anthropic use cycle (daily-annual); moreover, primary P mines are concentrated in few areas (China, Morocco, USA), mostly not belonging to EU, which imports more than 90% of its P demand [31, 32]. For these reasons, the sustainable use of nutrients, including P, is a priority for the recent EU strategies [7, 8].

On the other hand, along the anthropic use cycle, P is used with very low efficiency since there are P losses at every step of its life cycle, but it remains available in certain waste flows, from which it can be recovered and reused, according to the CE paradigm. Along the food value chain, there are three main waste flows characterized by high concentrations of P: animal manure, urban wastewater, and sewage sludge, and food processing waste flows, such as slaughters, other solid waste, and wastewater [33]. More than 30 technological processes, some of them commercially viable, have been already developed to recover P from several types of waste flows (e.g., wastewater, sludge, and ashes) in different forms (e.g., struvite, calcium phosphate) [34]. Although many opportunities for P recovery and reuse are available at the industrial level, the full-scale implementation of these technologies is still limited. Moreover, the presence of P in certain industrial waste flows is often perceived as an issue than an opportunity [35].

The EU project Prosumer, funded by EIT Climate KIC (2020) and coordinated by the authors, tackled the question about what elements are missing and necessary to unlock a wide diffusion of P recovery technologies at the industrial level. It emerged that the companies have not suitable tools and methods to transfer the interdisciplinary know-how developed by the scientific community in their contexts, translating it into quantitative information to support their decision-making process about P recovery. Consequently, within the project Prosumer, the authors provided an industry-oriented methodology, consisting of four main steps, to guide the companies in the identification of the most suitable P management pathway, according to their interests and business strategies. In this methodology, the ViVACE® tool has a fundamental role in providing structured data about P flows along with the industrial processes and in the waste streams, becoming useful inputs for other tools to evaluate the economic feasibility of potential investments in P recovery and other relevant KPIs. The Prosumer methodology and its application to an Italian food company are well described in [36]. **Figure 3** shows the setting of the ViVACE® tool representative of the annual quantity of P contained in the material flows both in the food processing and wastewater treatment plant. In this first application, it is shown the "first draft" of the tool, set with common software and manually, that means without using the official graphics, as in the following applications, with the aim to understand how it can be constructed. To fill the visualization tool, the annual quantities of P were evaluated, considering as stages different steps within the food processing and the wastewater treatment and analyzing the inputs and outputs of P contained in several flows (raw materials and other ingredients, final products, solid waste, wastewater, sewage sludge, etc.) within the boundaries of the company. The annual P flows (kg/year) were reported as a proportion of the maximum value that corresponds to the quantity of P that enters the food processing.

The setting of the ViVACE® tool allowed the evaluation of significant KPIs to measure the process and highlighted potential opportunities to manage P according to a CE. **Table 1** summarizes the relevant environmental and economic KPIs obtained from the application.

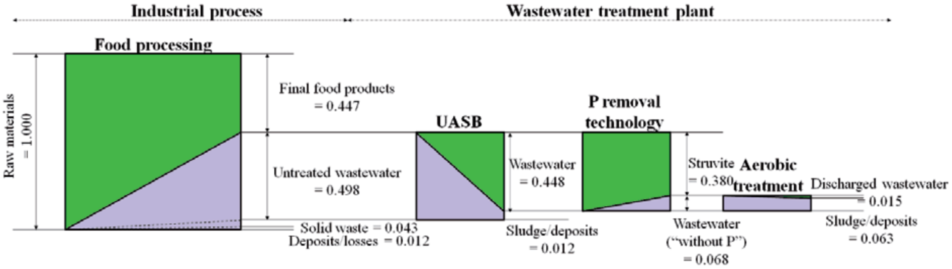

Figure 3.
Normalized annual P flows in the food company analyzed in the project Prosumer through ViVACE® tool [36].

Typology	KPI	Description	Value
Environmental	Final P concentration	P concentration in the discharged wastewater to be compared with the legislative limits.	6.6 mg/l
	P removal efficiency	It represents the efficiency of the entire wastewater treatment plant (WWTP).	96.9%
	P recovery technology efficiency	It depends on the technology and the operating parameters in the specific process.	80.1%
	P use efficiency	It represents the part of P that effectively remains in final products, comparing it to the P quantity that enters in the process.	44.7%
	P load coefficient	It represents the "impact" of final products in terms of final emissions of P in wastewater.	34.4 mg P/kg
	Unrecovered P	It represents the unrecoverable part of P, dispersed along the entire process.	13.6%
Economic	Specific costs per amount of recovered P	It represents the costs necessary to remove/recovery 1 kg of P with specific technology and plant.	0.864 €/kg P
	Incidence of P removal cost	It compares the cost incidence of P removal on the wastewater disposal.	5.39%

Table 1.
KPIs used to assess the sustainability of P removal/recycling from wastewater.

According to the economic feasibility study, fed by the collected quantitative data about P flows, it derived that, although the cost for P recovery covers a minor part of the wastewater disposal costs, the price for the selling of the recovered P, to make the investment sustainable, is greater than the cost of primary P rocks. This and other barriers to effectively shift to a more sustainable P management must still be addressed, as analyzed by recent studies [34, 35]. Nevertheless, with the applied methodology, the companies can have all the quantitative information to unlock, at least, an interest in evaluating and exploiting the opportunity to recover P from their waste.

2.2 Plastics sector

Plastic has been identified as a priority area in the new European CE Action Plan [7] due to its high complexity in the management of its waste and its negative impact if it improperly reaches the environment. Although its irreplaceable features, such as ease of processing, low weight and cost, and hygiene, the typical linear management of this material is no longer sustainable, above all when it is used for applications characterized by a very short service life, for example, the single-use plastics and the packaging. These specific functions are affected by a high production of waste, characterized by a low recycling rate in comparison to other materials (e.g., paper, metals, glass).

There are two major aspects that affect and limit a greater recycling rate for plastics. The first issue is related to the wide variety of polymers included in the typical waste flow to be managed. The second limiting aspect is linked to the downgrading of recycled plastic properties. Plastic waste flows containing only one type of polymer are quite easy to recycle. Every recycling process is studied and implemented to work with a specific polymer as an input material. In case the input

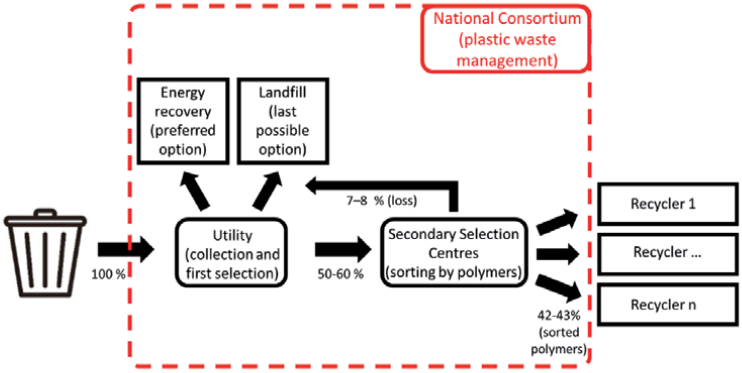

Figure 4.
Current Italian plastic waste management system and share of the main material flows.

flow is not contaminated by other types of polymer, the recycled plastics has good properties, even if a certain grade of degradation occurs.

In this scenario, the current Italian plastic waste management system is characterized by the described two critical issues. A national consortium, created to optimize the collection, recovery, and recycling of plastic packaging, manages the entire plastic waste system. It provides indications for different actors to manage several activities in the waste management process [37]. The territorial utility is the only one that can collect and carry plastic materials from urban and industrial waste. The utility does a first sorting phase from the plastic bin, sending the suitable materials (mainly packaging) to the following stages (50–60% of the entire flow). The remaining part, consisting of non-recyclable plastics, is sent to energy recovery (preferred option) or landfill (last option), according to the national consortium indications [38]. The flow selected for recycling is sent to a secondary selection center that has the technology to sort materials by polymer and by color. In this phase, another part of plastics waste (about 7–8%) is lost due to the sorting system inefficiency [39]. It derives that only 42–43% of the total amount of material collected in the urban plastic bin is sold to recyclers. Not all of this quantity is effectively recycled due to another inefficiency in the recycling process, which depends on the technological development of the specific plant. **Figure 4** shows the schematic view of the Italian plastic waste management system.

The current trend to eliminate the problems of plastics management is to shift to a “plastic free” model. However, for some applications, the replacement of plastics with other materials may not be the most sustainable solution, at least in the short term, considering environmental or economic aspects, or both of them [40]. A more promising solution, above all in the short term, could be shifting to an effective CE for plastics, capturing the maximum value of the resource through improved after-use plastic management [41]. With the aim to increase the collection, sorting, and recycling efficiency of the current waste management system, to minimize waste generation and resource use according to the CE paradigm, the authors’ team designed, implemented, and assessed two innovative circular initiatives for plastics, one applied to sports events (named #CORRIPULITO) and the second applied to the food value chain (named RICIRCOLA – Plastic Waste Free).

2.2.1 #CORRIPULITO: a sustainable model to manage plastic waste at sport events

The organization of sports events can generate both positive and negative effects on the host territory. A high amount of waste generated during these events, if not properly managed, can determine a negative environmental impact, above all plastics waste [42]. To reduce the environmental impact of sports events, the #CORRIPULITO initiative was designed and implemented in a small marathon to improve the management of plastic waste in comparison to the previous editions of the same event. In this specific context, four types of plastics were sorted and collected to increase the recovery efficiency of the management system, activating dedicated reverse logistics. A detailed description of the design and implementation of #CORRIPULITO is in [43].

The implementation of the ViVACE® tool allowed the assessment of the sustainability of the initiative, and particularly of the environmental and economic pillars, through the collection of useful and systematized data and their elaboration to evaluate significant KPIs. Also, the detailed steps for the implementation of the

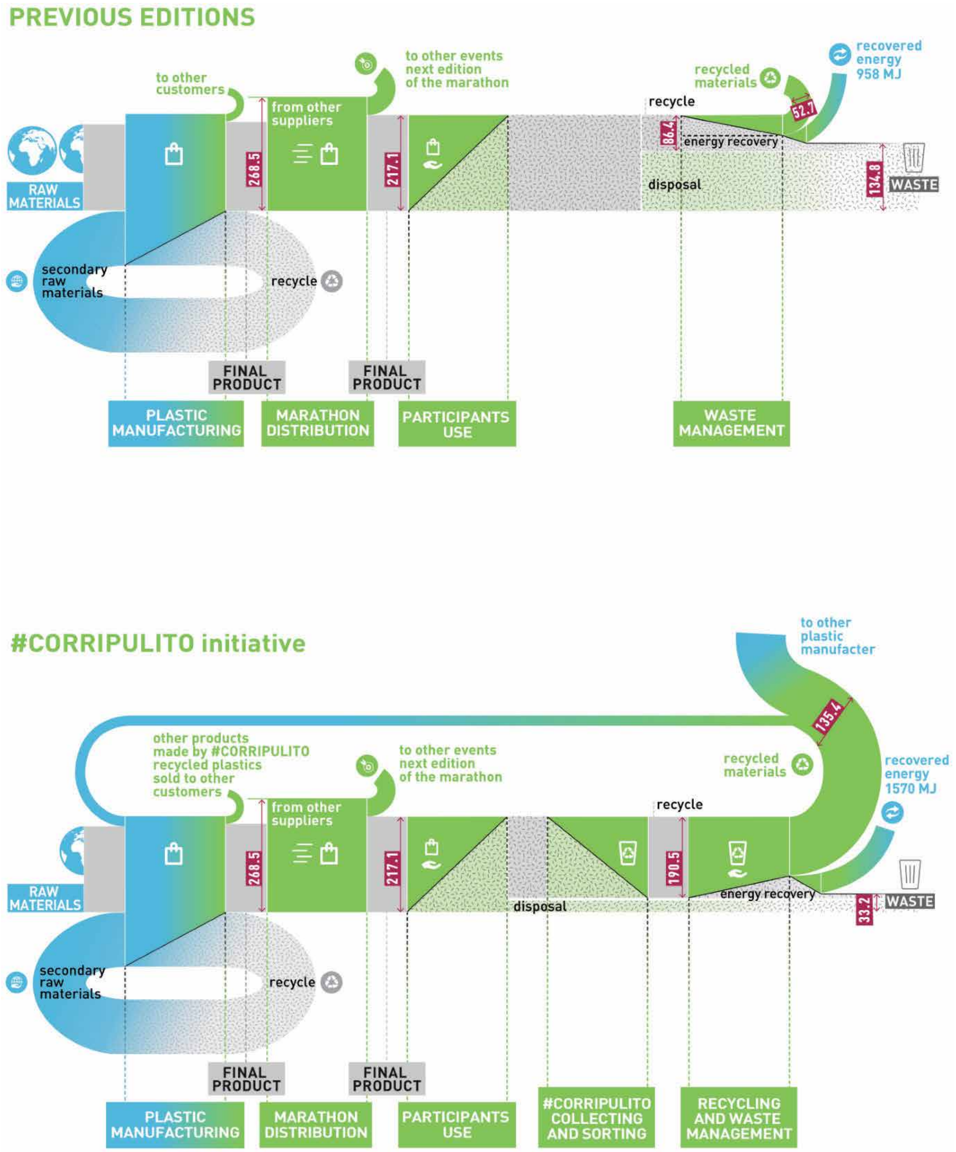

Figure 5.
Setting of the ViVACE® tool for the #CORRIPULITO initiative and its comparison to the previous editions of the sport event [43].

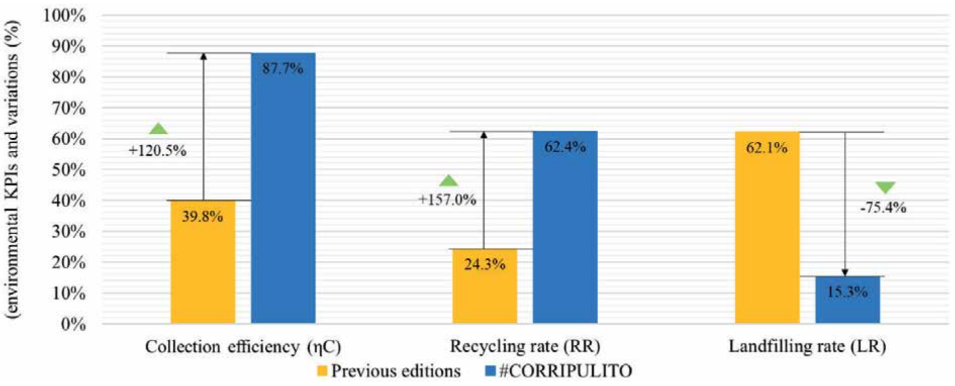

Figure 6.
Evaluation of environmental KPIs representative of plastic waste management [43].

ViVACE® tool to #CORRIPULITO are provided in [43]. **Figures 5** and **6** show the main quantitative results of the sustainability assessment, respectively as the setting of the visualization tool and evaluation of the selected environmental KPIs, comparing two scenarios (previous editions of the considered sport event and #CORRIPULITO).

2.2.2 RICIRCOLA: plastic waste free - an innovative management model for plastic food packaging

Among plastic materials, PET (polyethylene terephthalate) has become the most promising packaging material for food products, and above all for beverages, due to its excellent features, such as high clarity and good barrier properties towards moisture and oxygen, and also for its high potential for reuse after recycling process also for food contact applications [44, 45]. Currently, PET bottles, collected and send to the recycling process, are more than 50% of the consumed bottles, which is a very high rate in comparison to other disposed plastics. Bottles are not the only packaging in PET. PET trays (about 1/3 than PET bottle consumption, by weight – PETcore data) are widespread in food packaging applications, as they preserve and keep food fresh longer. PET trays contain almost 50% rPET, but they are typically separated from bottle flow and are very difficult to be recycled to a third life [46]. The consequence is a great loss of PET tray value after the food consumption phase.

With the aim to recover the value of plastic food trays, a new model for the management of plastic packaging in the food supply chain is proposed, based on the concepts of CE. The main idea at the basis of the new model, called "RICIRCOLA - Plastic Waste Free" is represented in **Figure 7**. It consists of the design of innovative plastic packaging, made with a mono-polymer (PET), having specific characteristics that allow: (i) the complete traceability from production to post-consumption phase through the insertion of a specific tracking element, particularly an RFID tag; (ii) the increase of collection and sorting efficiency through the involvement of the consumer who receives a fee if he brings back the after-use packaging at the collecting station, set up at the retailer; (iii) a simplified reverse logistics, ensured through the dedicated collection and sorting system that allows a single-polymer waste flow, with the aim to facilitate the recycling at the end-of-life, enlarging the applications of the recycled plastics. To assure all these features, an integrated value chain that comprises packaging the manufacturer, food brand owners, retailer, consumers, and the plastic recycler, was established, following a life-cycle thinking approach.

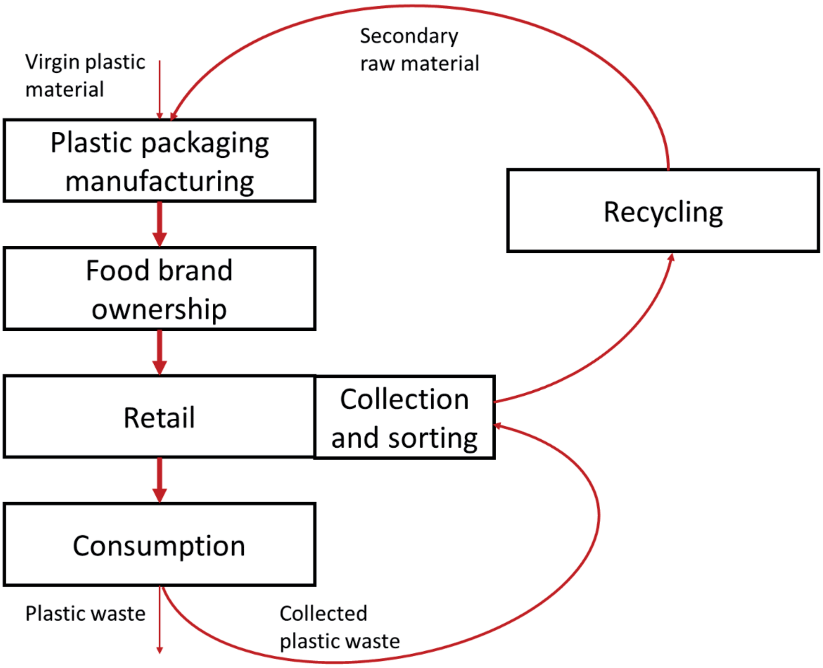

Figure 7.
Schematic framework of the novel management system for plastic packaging.

The proposed model was tested and validated in Emilia-Romagna (Italy) for two months (October–November 2020), redesigning the packaging for two food products distributed in three supermarkets, ensuring a fee of 0.20 €/tray for the engaged consumer. The collected plastics were sent to the recycler to manufacture other food trays.

Figure 8 shows the final set of the ViVACE® tool comparing three different scenarios: (i) the current management system of trays in Italy, (ii) the results obtained with the initiative "RICIRCOLA – Plastic Waste Free" after two months of experimentation, and (iii) the projection of the results after a year of implementation of the proposed model. The detailed description of the model and its results, assessed with the use of ViVACE®, is out of the scope of this chapter and is the subject of a dedicated paper under submission. However, it is possible to extract some relevant and macro quantitative information to compare the "RICIRCOLA - Plastic Waste Free" model to the current Italian waste management system. The results highlight that, in comparison to the current situation, considering the same quantity of collected plastics after the consumption phase, the innovative model "RICIRCOLA - Plastic Waste" should increase the plastic waste recovery efficiency of about +120%. The projection of the results achieved during the experimentation, after one year of practice, demonstrates that it could be possible to increase the recycled plastic quantity by about +126%, reduce the waste sent to landfill (−57%) and replace the 36% of virgin plastics with secondary raw materials. It derives that this novel model can really contribute to the achievement of the target for plastic recycling (55%), set by the European Strategy for plastics in 2030.

2.3 Textile/footwear sector

Due to the current production, distribution, and consumption system, the fashion sector is one of the most impactful since it is still completely based on a linear

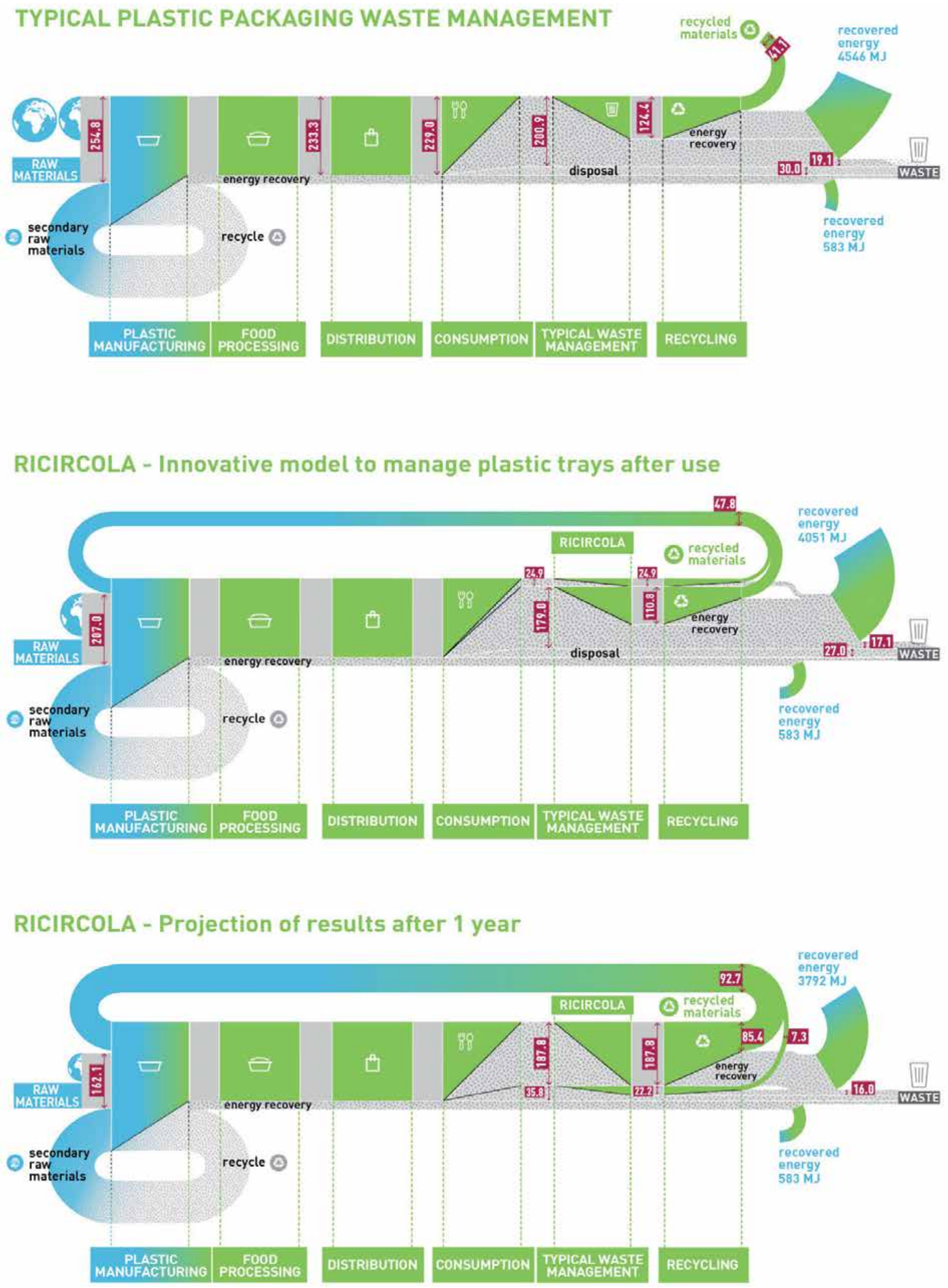

Figure 8.
Setting of the ViVACE® tool for the "RICIRCOLA – Plastic Waste free" in three scenarios: current situation, experimentation, projection after one year.

economy, generating a high amount of waste and high level of pollution for the manufacturing of products often characterized by a short life (due to the seasonality of materials and components linked to sudden changes in fashion trends) and difficult to be recovered [47]. Due to its negative environmental impacts, textiles are one of the priority areas of the new EU Circular Economy Action Plan [7]. In particular, some of the environmental issues generated by the textile/footwear sector are related to climate change and large use of non-renewable resources during production, and water pollution and the release of hazardous agents (e.g., microplastics) both in the manufacturing and using phases, problems that become more complex due to the underutilization and the low reuse and recycling rate of fashion products [48]. Moreover, the fashion industry is strongly affected by issues and potential failures related to reputation, above all in the luxury fashion industry of for very famous brands: poor labor conditions, chemical contamination of soil and water, workers' exposure to chemicals, and animal cruelty are some of the main problems perceived as unethical, which can change the external perception of the brand and its products [49].

The transition to a CE can really improve the current fashion sector, addressing both the macro-issues, which are the increase in resource efficiency and the reduction of the negative environmental impacts, and reducing the risk of reputation problems, through a specific feature of this sustainable economic paradigm, which is the traceability of the materials, ensured by digitalization [3, 15, 49]. However, there are some challenging aspects that limit this change.

(i) The fashion value chain is characterized by high fragmentation and the involvement of very different actors. Most of the companies involved in the fashion value chain are SMEs (small-medium enterprises) with an organizational fragility that does not prevent their operations at high-quality levels, but that limits their potential for growth in terms of product development and presence on the market. The figure is reflected in the difficulty of some companies to proactively face up to extremely topical issues, and the lack of digitization of resources which prevents the importance of issues such as waste reduction, chemical risk, transition to renewable energy, changing climate, and ecological handling. (ii) Fashion production, which has always been growing in recent years, has not been accompanied by innovative industrial policies, with a process that has always remained the same over the last decades, limiting the inclusion of innovations based on sustainability and circularity on products and processes [50, 51].

The lack of traceability and transparency in information about resource use determines these aspects [52]. The ViVACE® tool has been proposed to provide a snapshot of the current fashion supply chain, in the footwear district in Emilia-Romagna Region, with the aim to collect quantitative information about sustainability (environmental, economic, and social). The starting point for this application has been the analysis of the footwear assembler, the last manufacturing stage of this supply chain. Unlike previously described applications of the ViVACE® tool, in this case, the method has been implemented not to a single resource (see the P case study) or to products (see applications in plastics sector), but to entire assembling process, considering all the materials and other resources (e.g., energy, waste, water, logistics equipment, and transports) necessary for the final products. The main result of this application is a dashboard, fed by relevant KPIs about the process, able to guide the managers of the single operational units to monitor their performance. The preliminary application of the ViVACE® tool and the evaluation of relevant KPIs highlighted some criticalities and improvement pathways. Some of these have already been implemented in the analyzed company in terms of environmental sustainability, such as actions to improve energy management and reduce the use of hazardous materials. Also, from a social point of view, some actions have been developed, such as the elaboration and publication of an ethic code of conduct shared with all the suppliers. More detailed and quantitative results are not currently provided for confidentiality since the company wants to implement its own communication and dissemination campaign.

The same approach is now being repeated in the district for at least one actor of the supply chain or for more companies according to their expression of interest. In fact, the greatest impact on each pillar of sustainability will be ensured by implementing circular actions at the district/supply chain level.

Industrial sector	Brief description	Application approach
• Use of plastics in agriculture	The ViVACE® tool is used to assess potential solutions to make the use of plastics in agriculture more sustainable, for example: • improving the recycling of plastics anti-hail/insect nets; • replacing plastics with bio-based materials for mulching applications.	Tool applied to the products (see other plastics applications)
• Customized plastics/paper carrier bags	The ViVACE® tool is used to collect quantitative information to assess sustainability in three Italian companies in the selected sectors, with the aim to understand their current level of circularity and identify improvement pathways.	Tool applied to the process (see application in textile sector)
• Lighting system manufacturing		
• Machines for plastics manufacturing		

Table 2.
Application fields in which the ViVACE® tool is under development.

2.4 Other applications under development

The setting of the ViVACE® tool is under development in the other four applications at a starting phase. **Table 2** summarizes the main characteristics of these application fields.

3. Discussion and implications of the approach

According to the needs evaluated during the development of the new visualization tool, the versatility and capacity to be adapted to every product and industrial sector were fundamental and covered by only a few available tools in the literature. These features for the ViVACE® tool have been deeply demonstrated with the previous applications.

Providing a recognized classification of the analyzed applications is not easy in relation to the already mentioned fragmentation in defining CE and measurement methodologies [25, 53]. However, the authors propose a classification based on literature (both academic and grey literature and standards) that is already active about the proposition of a CE taxonomy with the aim to support the diffusion of circular actions, contributing to providing categories able to facilitate the development and access to finance, credit risk assessment, and transferability and replicability of projects, initiatives and investment across regions. In particular, four documents have been analyzed, integrated, and, when necessary, adapted to select useful proposed categories for the arrangement of the described ViVACE® applications in a framework able to specify its potential and adaptability. The analyzed documents are: one academic paper [54]; a report by the European Commission [53]; and two standards (BS 8001:2017, published; draft of the framework of the Italian project UNI1608856). **Table 3** explains the six categories selected from each reference to be used for ViVACE®.

According to this categorization, the ViVACE® tool applications can be characterized as in **Table 4**.

The main feature that characterizes the ViVACE® tool, which is well explained in **Figure 2**, is the integration of a bottom-up approach, considering what the practical actors of CE (mainly the industrial sector) need to define strategies to

Categories	Brief description	Options	Reference
Purpose	It describes the possible use of the ViVACE® tool and its results (adapted from "Usages").	• Improvement • Support for decision-making • Comparison (linear/circular) • Benchmarking • Communication • Certification • Etc.	[54]
Loops	It describes the typology of circular actions that is implemented.	Due to the fragmentation in this context, only the 14 categories defined in [53] are used, to limit the options.	[53, 54] UNI1608856
Supply chain stage	It describes the actors of the supply chains involved in the application.	• Design • Suppliers • Manufacturing • Distribution and sales • Use • End-of-life • Transversal	UNI1608856
Finding formats	It describes the outputs obtained/derivable by the ViVACE® tool (it is not strictly connected to "Format" used in [54]).	• Sector-specific KPIs • Managerial dashboard • LCA • Net Present Value • Etc.	[54]
Level	It describes the scale of the application.	• Micro (single company, products, consumers) • Meso (supply chains, symbioses, districts) • Macro (city, province, region or country)	[54] UNI1608856
Principle	It describes the basic principles on which the applications are designed.	• System thinking • Innovation • Stewardship • Collaboration • Value optimization • Transparency	BS 8001:2017

Table 3.
Categories adapted from the literature to describe the ViVACE® tool applications.

shift to the circular paradigm. In particular, this need is the availability of intuitive and quantitative information. The main novelty and strength of the ViVACE® tool are its capacity to starting from a lower level than the availability of information, which consists of the availability of all necessary data to obtain information. In practice, the ViVACE® tool simply "forces" the users to collect data in a structured and systematized form. The framework of the necessary data has been structured starting from knowing how the companies work (with materials and processes characterized by efficiencies and the use of energy, water, logistics, etc.), and since,

ViVACE® tool applications	Purpose	Loops (code used in [53])	Supply chain stage	Finding formats	Level	Principle
Phosphorus management	Support decision-making	Deployment of technologies for CE (1.c)	Manufacturing	Sector-specific KPIs/NPV	Micro	Stewardship
#CORRIPULITO	Comparison	Separate collection and reverse logistics of waste (3.a)	Transversal	Sector-specific KPIs	Meso	Collaboration
RICIRCOLA – Plastic Waste Free	Comparison	Design and production of circular products (1.a)	Transversal	Sector-specific KPIs	Meso	System thinking
Textile/footwear sector	Improvement/ Communication	Deployment of tools enabling CE strategies (4.a)	Manufacturing	Dashboard/LCA	Micro → Meso	Stewardship/ Transparency
Plastics use in agriculture	Improvement	Substitution or reduction of substances to enable CE (1.d)	Use/End-of-life	Sector-specific KPIs/LCA	Meso	Innovation
Carrier bags manufacturing	Improvement/ Communication	Deployment of tools enabling CE strategies (4.a)	Manufacturing	Dashboard	Micro	Stewardship
Lighting system manufacturing	Improvement/ Certification	Deployment of tools enabling CE strategies (4.a)	Manufacturing	Dashboard	Micro	Stewardship
Machines for plastics manufacturing	Improvement/ Communication	Deployment of tools enabling CE strategies (4.a)	Manufacturing	Dashboard	Micro	Stewardship

Table 4.
Categorization of the ViVACE® tool applications.

independently from products, processes, and sectors, but also from size, the organizational structure and functions of industries are very similar, the tool can be easily adapted to different contexts. Therefore, this approach results more promising and effective than imposing a set of KPIs to measure circularity (top-down approach), since the lack, inconsistency, low quality, and unreliability of certain data could generate a partial, inconsistent and misleading evaluation of indications, difficult to understand and compare [23, 55].

The further step of this proposed approach, which starts from the bottom level, is to tackle another identified issue, which is the complexity to shift from one scale to another [22]. The micro-scale KPIs are typically based on physical parameters and linked to technological aspects, while high-level indicators, such as socio-institutional indexes, climate change, and the targets defined by the SDGs, require a combination and integration of a set of KPIs used for the monitoring of CE [55]. Clearly identifying the set of KPIs and the way with which combining them is a challenge, but assessing the macro level is fundamental for the establishment and monitoring of policy coherence and achievement of the targets at regional, national, and international scale. Probably, the use of multi-criteria decision-making methods, as tools able to solve complex problems by simultaneously taking into consideration multiple and different criteria, could be the solutions, as already proposed for the definition of circular business strategies in [56] (micro-level application). In particular, the authors are currently working on how to aggregate KPIs used in the described applications of the ViVACE® tool to evaluate their contribution to important international strategies, such as the new EU Circular Economy Action Plan, the Green Deal, and the SGDs.

The main implications of this work are four-fold. (i) Firstly, it describes a comprehensive research method able to overcome the gap identified in shifting from CE theory to practice, which is the lack of clear and consistent approaches to actually assess the circularity and sustainability of products, processes, business models, and strategies. The flexibility and versatility of the proposed tool, as demonstrated by different applications, concerns the systematization of data collection to make data available for the evaluation of useful information and KPIs. Consequently, as demonstrated by this study, the ViVACE® tool is a promising and effective means to activate the evaluation, and widespread use of relevant KPIs collected in literature [19, 22–24]. The applications of the ViVACE® tool also provide a series of quantitative information about the involved sectors and/or initiatives, most of them not still available. Consequently, they can guide researchers in the design and development of improving solutions (products, processes, technologies, etc.). (ii) The second implication of this research involves the industrial managers and other practitioners, such as consultants. According to the purposes showed in **Table 2**, the companies can use the ViVACE® tool to evaluate and monitor useful, intuitive, and quantitative information to improve their processes, products, and businesses, in terms of sustainability, to compare them with competitors and to externally communicate (e.g., to costumers and/or to obtain certifications) their current results, and strategies to advance their situation achieving some targets. (iii) The third implication, applicable at micro level as the previous ones, is linked to providing support for public and private financial bodies. Since the ViVACE® tool is able to measure the potential of different CE actions and scenarios applied to several industrial sectors, it can be used to compare different opportunities to be funded, guiding the decision towards the most sustainable and less risky solutions. (iv) Finally, the ViVACE® tool has the capacity to arrange micro-level information, which, if suitably aggregated, can be used to evaluate the contribution of micro-level CE activities on regional, national and international policies. At macro-level, institutions and policy-makers could use the tool to simulate the scenarios potentially prepared by some policies and incentives, to support the consistent and robust design of these tools to boost the transition to an effective CE.

4. Conclusions

The transition to a circular economy, as a more sustainable and resilient production and consumption model, is increasingly urgent: it will not consist only of an opportunity, but it will be fundamental at different scales for companies, institutions, and governments. The actors able to make this transition effective could collect the benefits of greater competitiveness since before. Since the delineation of this transition is not easy, also due to the nature of the circular economy, typically cross-sectorial and activated by a network of different actors, it becomes very important to have available information to quantify benefits and risks, compare different options, and hence support the decision-making process. The proposed tool ViVACE® has been demonstrated to be able to provide this quantitative information through its adaptation capacity to different industrial sectors and CE actions. Its applications in different contexts, and the types and formats of results that it is able to provide, opens new potential functions and also highlights limits in certain uses and specific needs to be solved and integrated with enhanced versions of the tool. Consequently, deep use of the tool will allow it to become more robust and consolidated, even if some of its features already result in innovation and are still not covered by any other available tool.

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Chapter 6

Understanding the Stages of the Product Life Cycle

Chinonso Kenneth Udokporo

Abstract

Originally formulated in the context of biological studies, the Life cycle (LC) concept was and now has become widely adopted as a framework for the interpretation and evaluation of phenomena that are subject to, and bound by the inevitability of change. The application of the LC concept to the development of industrial products is an important element in the administration of technological innovation. On this basis, therefore, it is referred to as the product life cycle (PLC). The concept of the PLC is used to support decision making in the management of product development. It may also be used in corporate strategy development, as well as the planning of activities and can be adapted to focus on technology deployment.

Keywords: product life cycle stages, introduction, growth, maturity, decline, management

1. Introduction

The management of the product development process is supported with the adoption of the product life cycle (PLC) concept, which is used as a decision-making tool. The PLC is used to describe the performance of the product as it advances through its life phases, from initial development until it is retired in order to fully exploit the utility of and the possibilities for profit at each phase of the life cycle [1]. While the product is in the market, the PLC phases are: introduction, growth, maturity and decline. With this in mind, the PLC becomes a representation of the product's market history and each phase is characterised by the trend of sales volumes and profit performance [2]. This supports the managers' decision-making efforts regarding possible intervention strategies – marketing arrangements to be taken, pricing considerations, product replacement, etc.

Given that the environmental performance of a product throughout its life cycle is influenced by the interaction between all the actors involved, an effective solution to deal with the environmental concern has to be considered in the context of the whole community of participants [3].

Ref. [3] states that with the consideration of the principles of industrial ecology, the activities of the community of participants should as a matter of urgency be considered within the context of the global ecosystem which comprises all living things, all land and water resources. Therefore, environmental analysis pays rapt attention to the life cycle of a product linked with all of its physical reality until it is disposed of.

Therefore, for an in-depth analysis focused on evaluating and reducing the environmental impact of a product, it is important to consider the manufacturing phases as well as the phases of preproduction of materials, use, recovery and disposal [3].

Considering environmental analysis, the product-system according to [4] is characterised by flows of resources transformed through the various processes comprising the physical life cycle. The LC processes that exchange substances, materials and energy with the ecosphere are the inevitable outcomes of the environmental impact of this product-system. According to the author, the different effects produced are in 3 main typologies:

1. Depletion – The exhaustion of resources, imputable to all the resources taken from the ecosphere and used as an input in the product-system.

2. Pollution – The totality of the events of emission and waste, caused by the output of the product-system.

3. Disturbances - The totality of the events of variation in environmental structures due to the interaction of the product system with the ecosphere.

Ref. [5] explored the possibilities of using the PLC concept in the management of private labels. Considering that private labels belong to a particular product brand, it becomes imperative to modify some aspects of the PLC, as it was developed on the basis of producer brands. For example, during the growth phase of the PLC, retailers expand brands to various product categories and apply the push approach while producers have an inclination towards widening their delivery network in the growth of their product brands and largely use the pull approach to achieve this. Also, there is a slight swing in focus from low-price strategy, mostly used in the introduction phase, to improving the quality and value in the subsequent stages of the PLC [5].

Ref. [6] emphasised the significance of considering the application of the PLC concept by procurement managers as increasing demands on cost reduction, supply sustenance, materials quality and the incidence of quickly changing technology and harsh competition have considerably expanded the scope of procurement, and elevated its significance at the corporate level [7].

2. Product life cycle stages

The PLC considers the features of a product(s) in terms of its LC. The life cycle theory is accepted as a decision making tool in management (of organisational structures of manufacturing activities; market analysis and forecasting based on the advancement of technologies; and the development of novel products and their introduction to the market) [3]. In light of this acknowledgement of the PLC concept as an analytical framework, there is the appreciation that both manufacturing activities, technologies and products themselves, theoretically develop as a result of an evolutionary route passing through different phases [3].

In the context of product management, in relation to market dynamics, the life cycle according to [3] is understood as the period during which the product is in the market. Refs. [6] in [8] suggested that the PLC is the fundamental variable in determining a workable business strategy. The PLC identifies the following successive four stages through which products progress [8–11].

2.1 Introduction

This phase occurs once a new product is conceived, fabricated and made available in the market [12]. This stage requires substantial investment because the product has to be accorded the best opportunity to yield profit. The characteristics of this phase are a small market; low sales (as could be observed by a gentle upward slope in the classical PLC curve), and high cost of research and development. The beginning of this phase is also characterised by losses made before substantial gains start to be actualized as the product sales increase. Depending on the product type/category, the introduction phase may also be characterised by very little competition and high prices. Ref. [13] states that the main order winner (OW) at the introduction stage is lead time (time from concept to availability of design) and capability of design.

2.2 Growth

As the product enters this phase, it experiences rapid gains, which is indicated by a sharp rise in the classical PLC [12]. The main characteristic of this stage according to [13] is increasing demand and that the main OW is service level (the ability of the product delivery system to respond to unpredictable demand). Marketing and promotional activities are effective ways to generate/enhance customer demand. Other obvious characteristics of this phase are an increase in competition, lower prices (as a result of competitors entering the market), reduced support costs (due to production increasing to meet demand) and increase in profits (as a result of reduced costs).

2.3 Maturity

At this phase, the PLC curve begins to flatten out, organisations are more concerned about maintaining their share of the market, and therefore the mere existence of the product is not given a second thought. The maturity stage is known to last longer than others [12] and is characterised by a drop in sales, more competition, a reduction in market share, a reduction in profits, further reduction in costs, innovation (aimed at improving market share). Ref. [13] indicates that the main OW is cost after the product at this stage has been pushed to a kanban supply chain.

2.4 Decline

The market becomes saturated at this phase, demand for the product and hence sales start to witness a reduction in demand and sales, however, the rate at which the declines occur can radically differ from one product to another. The decrease in sales for some products may tend towards zero, while others remain at a steady low level for longer periods [12]. These disparities show that the end of the PLC curve may take on a variety of forms. This could be seen as the beginning of the end of the product. At this phase, costs see a further reduction, demand reduces, the market starts to decline as competitors gradually withdraw, sales volumes drop, profits are seriously affected and the product is ultimately withdrawn from the market.

Several other PLC models other than the classical PLC curve are found throughout literature. For example, [14] identified three PLC stages and three levels, namely, pre-development, development and post-development. The three levels are business level, product level and component level. The pre-development stage is concerned with the conception and diagrammatic representation of the product. Development deals with the physical representation of the product through research and prototyping. The post-development stage is concerned with production, sale and use of the product.

Ref. [15] identified three stages of the PLC namely, pre-use, in-use and post-use. The pre-use stage covers the life of the product from conception to the delivery. The in-use stage concerns the period when the product is being used by the customer.

The post-use stage comprises the period when the product's functional life at the hands of the customer has ended.

Considering these phases, the objective of the PLC theory is to describe the behaviour of the product from the start of its life until it is retired, so as to improve the value of and the chances for revenue [1] and to appropriately allocate resources. Therefore, the LC is seen as a depiction of the product's market history and each phase is characterised by the trend of sales volumes, demand and profit performance [2]. This helps guide the managers' decisions regarding possible intervention strategies – marketing actions to be taken, pricing decisions, product substitution, etc. Again, considering the product as an item that comprises both the intangible dimension (need, concept and project) and a tangible dimension (complete product), its LC can be understood as a pre-established arrangement of evolutionary phases wherein each phase is necessary for the execution of subsequent phases.

PLC has been identified as the fundamental variable affecting business strategy [5] as it provides an important perspective for the formulation of strategies [8], because each phase has distinct characteristics that affect the operation of a business. What may be necessary in one phase may be unimportant in another [8, 16]. That is to say that each of the product life cycle stages brings different challenges, opportunities and problems; therefore, it is necessary to adjust marketing, financial, product, sales and human resources accordingly to make the product as successful as possible [11] in [5]. Again, the classical PLC curve is bell-shaped and represents sales in the course of time through the four stages described above. Such a shape of the product life cycle curve is an inevitable theoretical generalisation because, in practice, different products have different life cycle curves, depending on the length of individual phases and the very product type.

The significance of the PLC is reflected in the idea that it directs attention to the market opportunities and threats that may have strategic implications. The PLC is a resourceful framework for formulating contingent hypotheses about suitable alternative strategies [13] in [17] and directing the attention of senior management towards the anticipation of the possible consequences of the underlying dynamics of the market being served. Ref. [18] argued that the PLC concept does offer a beneficial and challenging framework for a meaningful evaluation of the growth and development of a new product, a business, or an entire industry. Ref. [19] believe that differentiated competitive advantages should be formulated, and are necessary at different stages in the PLC.

3. Detecting PLC stages

The PLC would be more useful in strategy planning, but only if the time when a product changed from one PLC stage to another can be more accurately and unambiguously predicted [20]. However, there is not yet a consensus on the methodologies for identifying each PLC stage [21]. According to [22], there are very few generic quantitative analyses on how to determine the bounds of each stage. The same authors stated that 'owing to a lack of established phase identification methods, a few authors concluded that the model is useful for monitoring sales but is limited to forecasting [22]. Ref. [23] states that proof of the PLC as a concept is difficult to find and that the PLC tends to be limited in its applicability. However, the same authors acknowledged that the qualitative descriptions of the stages can be more easily recognisable.

Despite the doubts and inconsistencies inherent in the PLC concept, [23] believes that it has become one of the building blocks of management theory in general. Ref. [11] also believe that PLC is likely a fundamental variable affecting business strategy.

Ref. [20] was able to identify the take-off point in the sales of colour television sets, or the transition from the introduction stage to the growth stage by using semilog paper to plot annual sales of colour sets as well as number of homes equipped with colour television, a difference analysis relative to the saturation of colour televisions.

An examination of the percentage change in real sales of a product from year t to year t+1 was performed by [24]. The authors assuming that the distribution follows a normal function plotted the observed changes as a normal distribution with mean zero; they also determined that if a product had percentage change less than $-{}^{1}/_{2}\sigma$, it was observed to be in the decline stage. A product with the percentage change exceeding, ${}^{1}/_{2}\sigma$ was in the growth stage. And if the percentage change was in the region $\pm{}^{1}/_{2}\sigma$, the product was said to be stable corresponding to the maturity stage.

Ref. [24] believe that their work is a good model of sales behaviour in certain market situations. However, they advised that the results of the tests conducted in it be interpreted with caution as many of the product forms are not sufficiently detailed. The performance of the model leaves some questions regarding its general applicability. Ref. [24] also acknowledged that many complex interacting forces affect sales. Forces such as seasonal fluctuations are not relevant to the LC model while rapid declines in currency (example: the dollar) value through inflation may cause changes seem to reflect the LC patterns but are in fact independent of them. Hence [24] adjusted all sales data used for their work to make provisions for population growth, change in the level of personal consumption and price changes.

Ref. [23] argues that [24]'s work appeared mostly anecdotal, or focused on a very small cluster of examples. Though [23]'s work did not concentrate on detecting the stage of the PLC (is focused more on brand life cycle-stability and durability), it sought to solve the problem of limited number of examples by adopting a much larger sample size from data collected by the British Marketing Research Bureau (BMRB) as part of their Target Group Index (TGI) and monitored over a longer period of time. The size of the TGI covered 25,000 British adults and this allowed a large number of brands to be monitored with some degree of comparability and accuracy in terms of questions asked and sample selection over a much longer period of time-20 years. Ref. [23] believes that the lesson learned from the PLC concept and its accompanying body of research is that it is perilous to ignore change. By extension, change could be the differences in life cycle stages and or the change from one life cycle stage to another.

Ref. [25] in [22] introduced the two measures of product life – catalogue life and, and commercial life – to determine the traditional life cycle model (M-PLC) stages in an investigation of the ethical drug industry in the U.S.A. Below is a summary of both [25] 's and [24]'s stage identification criteria (**Table 1**).

A forecast methodology was proposed for predicting both product life time (PLT) and non-linear PLC by [26], based on a two-stage fuzzy, piecewise regression analysis model. The authors applied a generation-based approach, which predicts PLC by deriving the annual fuzzy regression lines, based on the yearly shipments of earlier generation of products. It is possible to apply the proposed methodology in forecasting other multiple generation products like personal computers and semiconductor processes. Furthermore, the outcomes of the authors' prediction methodology can be applied as a basis for policy foresight and strategic definitions for each stage of the PLC. The authors of this work used historical data from consumer electronic components makers to conduct its empirical study assert that their proposed method successfully predicted PLT and PLC based on the available data.

Phases	Ref. [24]	Ref. [25]
Introduction	S_i less than 5% of peak sales	Up to 5000 new prescriptions in a single month
Growth	S_i^* greater than +0.05	From 5000 new prescriptions in a single month
Maturity	S_i^* in the +0.05 to 0.05 range	From maximum monthly revenue
Decline	S_i^* greater than −0.05	Below 20% or 10% of maximum monthly revenue
Symbols: Si = yearly sales of nondurable i divided by sales of all nondurables; Si = yearly percentage change in Si.*		

Table 1.
Adapted from [22].

They also acknowledged that uncertainties always exist in marketing information as a result of errors, biases, or intentionally designed fault data.

Ref. [27] acknowledging that econometric tests of all the hypotheses on the form of consumer good PLCs have not been carried out at the time adopted a more mathematical method, providing several methods of estimating PLCs. One of the methods provided by [27] is [28]'s generalised least squares method which is plagued with some disadvantages as there is no description of a method for the derivation of significance limits for the parameters. Another problem with Marquardt's method is the difficulty in implementation.

Another method developed by [27] Brockhoff, (1967) is the iterative method which according to the author, provides a good foundation for [28]'s generalised least squares method. This method provides a good starting point, in that it helps eliminate the problem of parameter limits encountered in Marquardt's method. However, it may still be riddled with the other limitations identified with Marquardt's method beyond the parameter limits problem.

Ref. [29] discussed the purpose and usage of the PLC regarding the consumer durable goods industries. The authors focused on a model that could forecast the industry volumes of a newly introduced product through each stage of its life cycle. The model or industry volume is the sum of the original purchases and replacement purchases as given by:

PLC = (Original Purchases) + (Replacements).

$I_{t0} = [(U \times S)_{t0} - (U \times S)_{t-1}] + K[(U_{t0} \times S_{t0})$.

I = Total industry volume.

U = Universe (Example: households or demographic segments).

K = Replacement constant [$K = 1/n(R)$].

S = Saturation.

R = Percentage of owners who will replace.

n = Number of periods to replace.

t_0 = Current period.

t_{-1} = First preceding period.

According to [29], product sales volume is composed of two elements: initial purchases or saturation of the product's target universe, and replacements of worn out units, been broken units or obsolete ones. In the early PLC stages, initial purchases constitute the majority of sales volume; however, as ultimate saturation is reached, the replacement component usually becomes dominant.

Ref. [20] reports that that some researchers due to the problem of management having to make different decisions at each LC stage, proposed a different set of forecasting procedures. The evidence used to support these as [20] identified are two products of Corning Glass Works – glass components for colour television tubes and cookware. The reviewing authors cautioned that the recommendations of such works are grounded on inadequate empirical evidence, noting also that the user has to know the PLC stage the product is in before the corresponding set of forecasting procedures can be adopted.

Other researchers according to the same review by [20] developed new product models which forecast the growth and maturity stages of a new product based on either test market data or pre-test research. However, these models are limited in accurately forecasting the second half of the PLC curve [20].

Some other authors/researchers chose to ask the companies producing, managing and marketing the products which life cycle stage their product(s) was in after carefully describing the product life cycle stages and their corresponding characteristics to the respondents. Where the respondents are fully engaged with the product (production managers for example and more closely so in the case of this research); i.e. overseeing a production process, drawing up and implementing a production schedule, managing costs, supervision duties, team building/management and as discovered through this research, duties more closely integrated with functions such as marketing, sales as well as finance this method of LC stage detection could be dependable because the respondents have sufficient relevant knowledge. However, this method could be subjective especially when there's not ample knowledge on the part of the respondents for a number of reasons which may include time spent in a particular company and managing a particular product or group of products.

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Globalization and increased competition are forcing companies to review and improve their production processes to be more sustainable. However, a clear vision and environmental culture are lacking because, even today, companies are motivated to act to improve the environment essentially by compliance with government regulations and the opportunity to achieve profit growth. This book presents practices, challenges, and opportunities for the digital and sustainable transformation of business as we know it.

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